A journey in particle physics:

From precision measurement of the heaviest particle to new physics search with the lightest (charged) particles

Costas Vellidis

Fermilab

University of Pisa seminar, July 21, 2016

Outline

Top quark mass measurement at CDF

- ❑ Top mass status
- ❑ This measurement
- ❑ Method
- ❑ Prospects
- ❑ Summary

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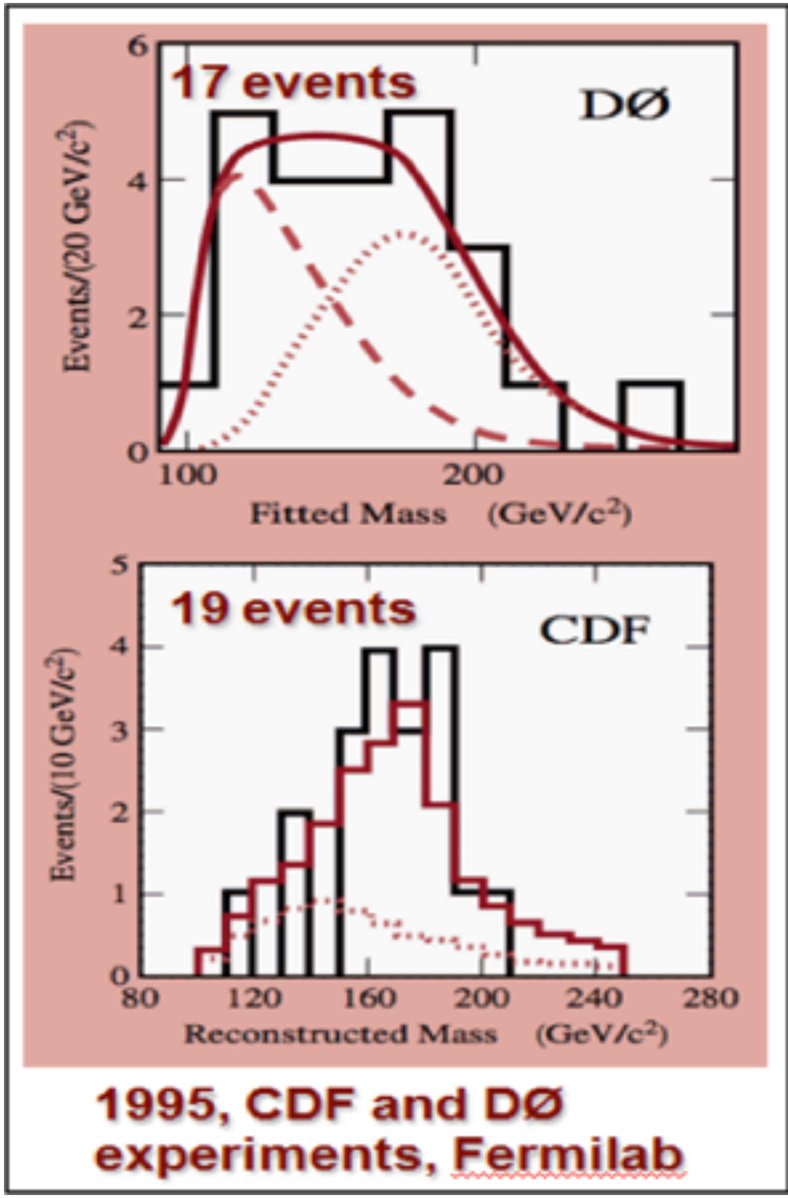
Search for neutrinoless muon-to-electron conversion

- Motivation
- Experimental technique
- Magnetic field studies
- Summary

Top mass measurement in the semileptonic decay channel using the full CDF sample

Basic facts about top

✓ Discovered at the Tevatron in 1995



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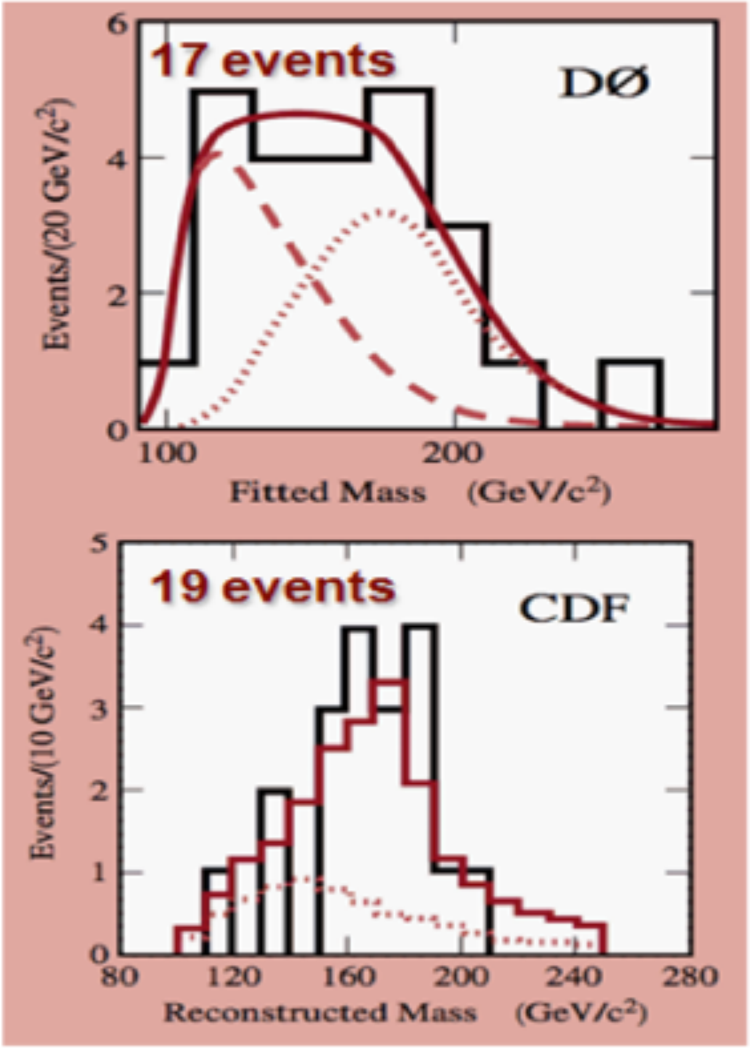

1995, CDF and DØ experiments, Fermilab

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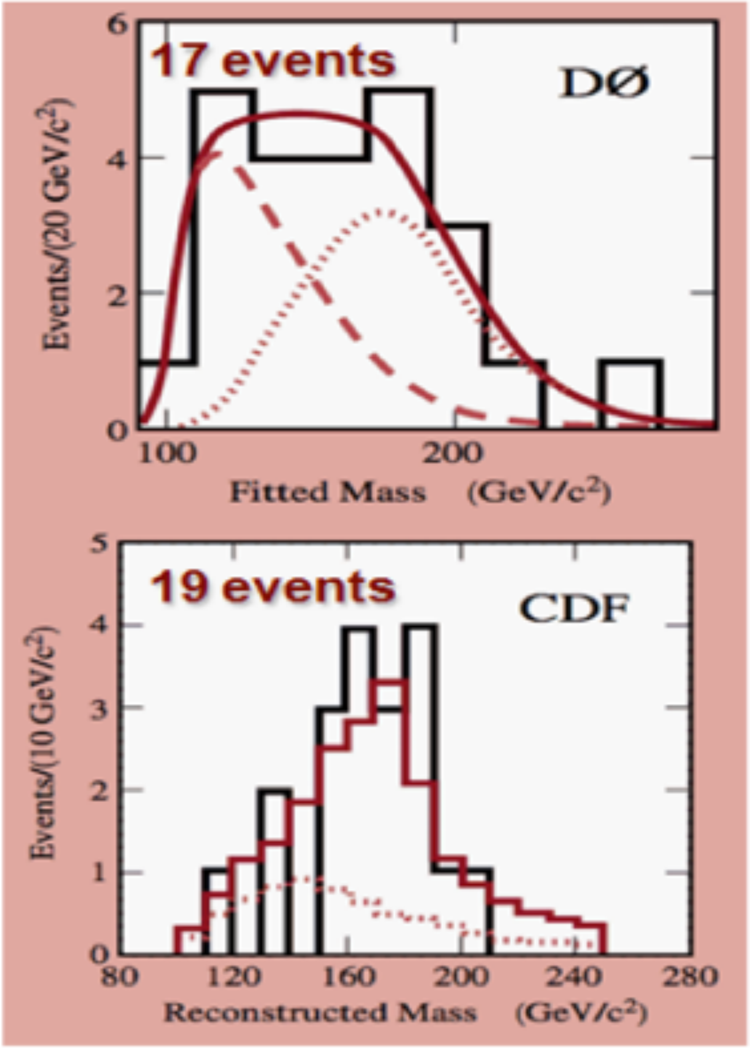

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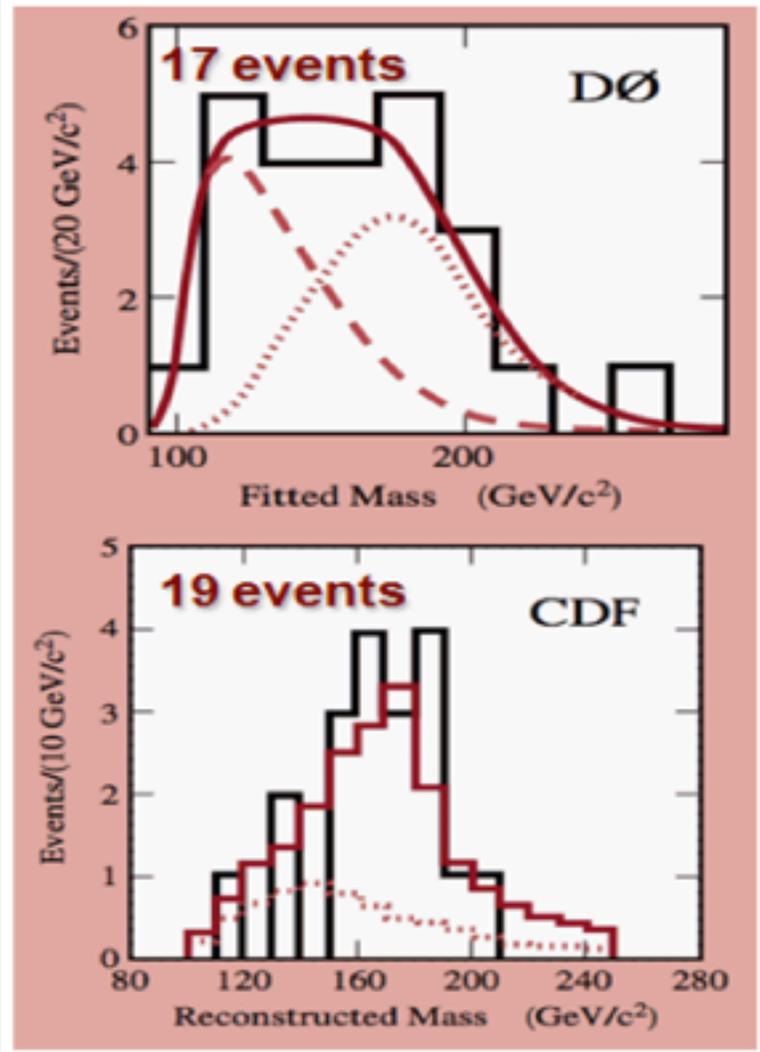

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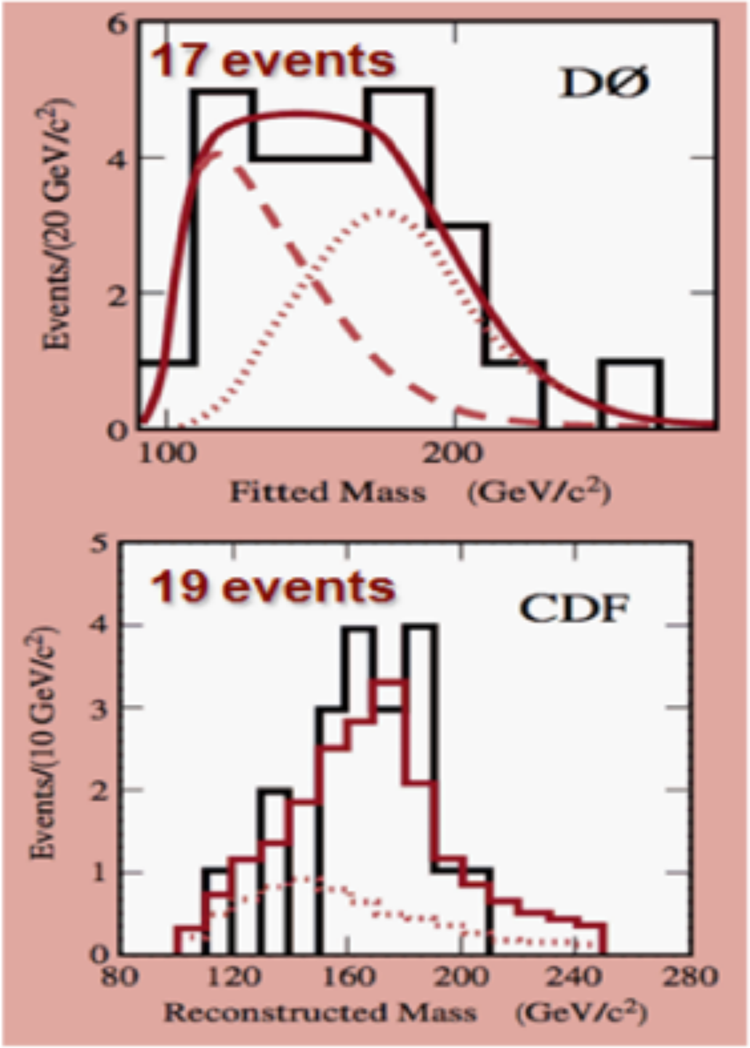
- ✓ Top physics (mainly) described by pQCD
- ✓ But top is colored and unstable particle: non-perturbative effects enter through the back door



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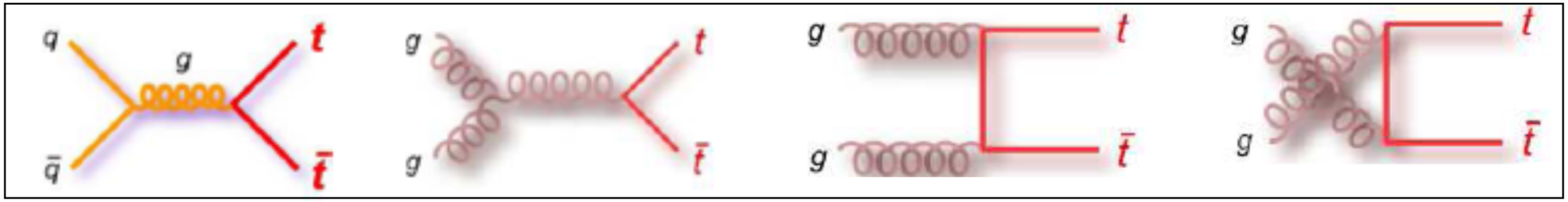
Top pair production and decay

Produced mainly through the strong interaction:

$\sigma \sim 7$ pb (Tevatron)



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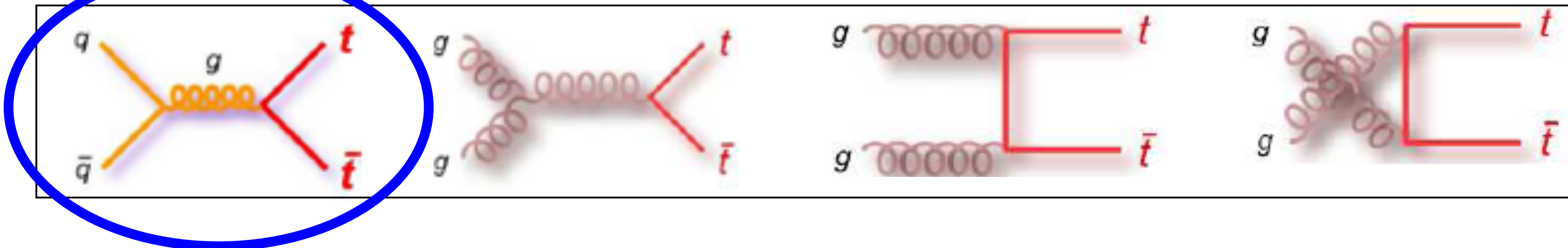

$\sim$85% at the Tevatron

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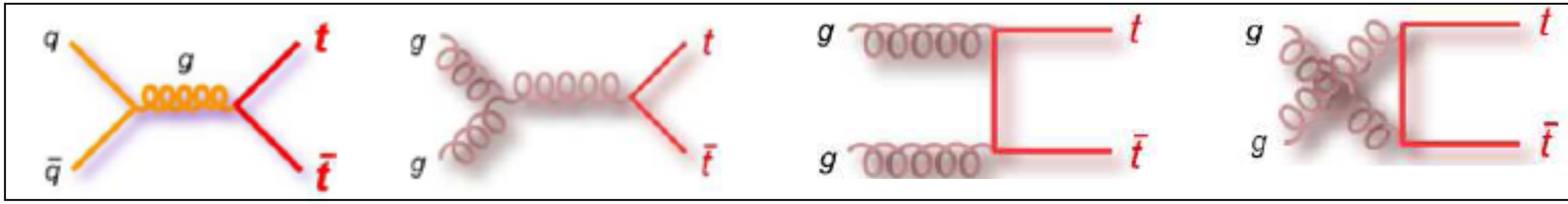
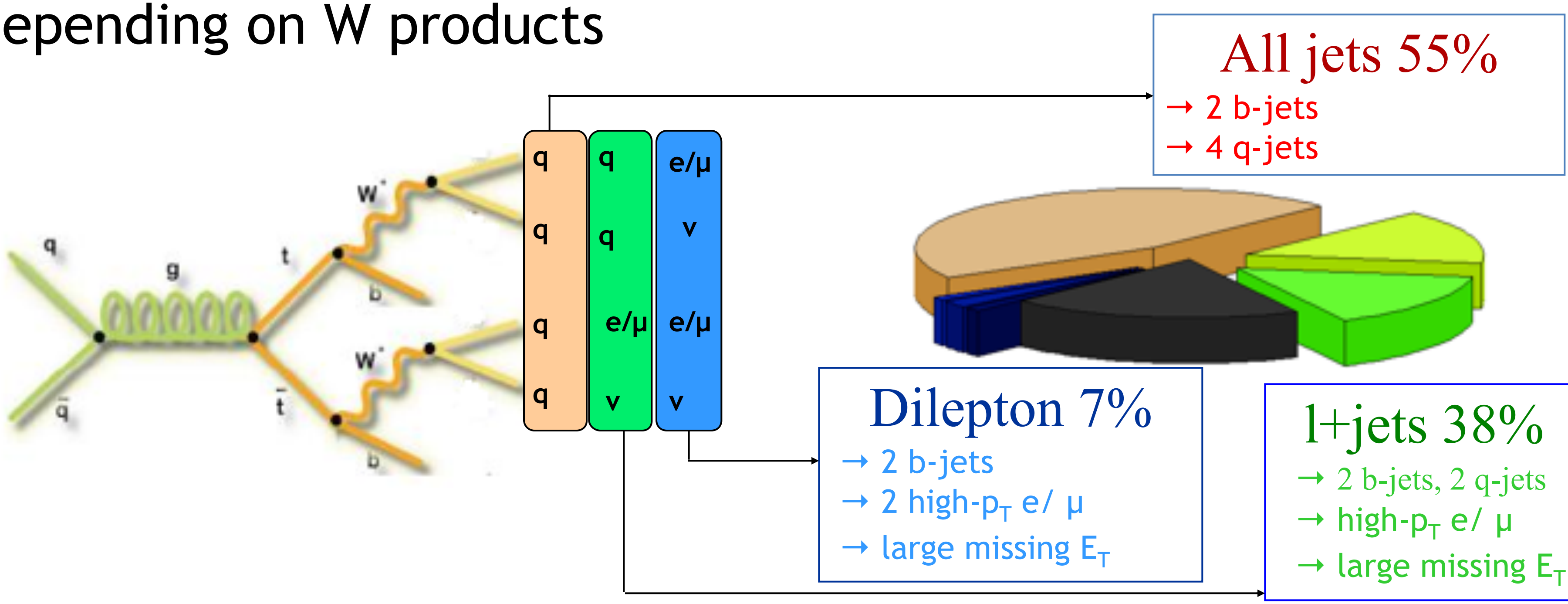


Decaying in Wb ~100% → 3 possible signatures depending on W products



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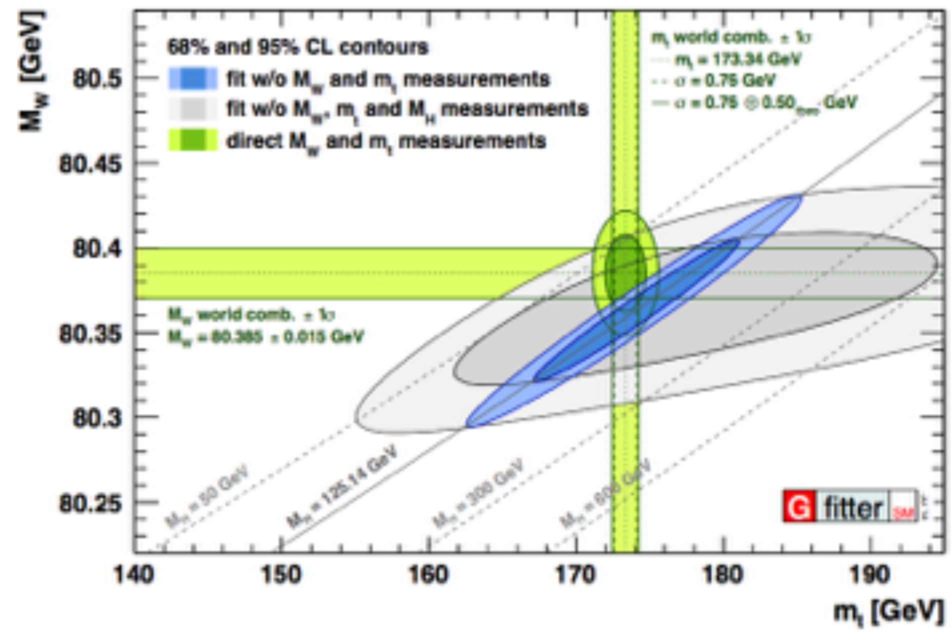

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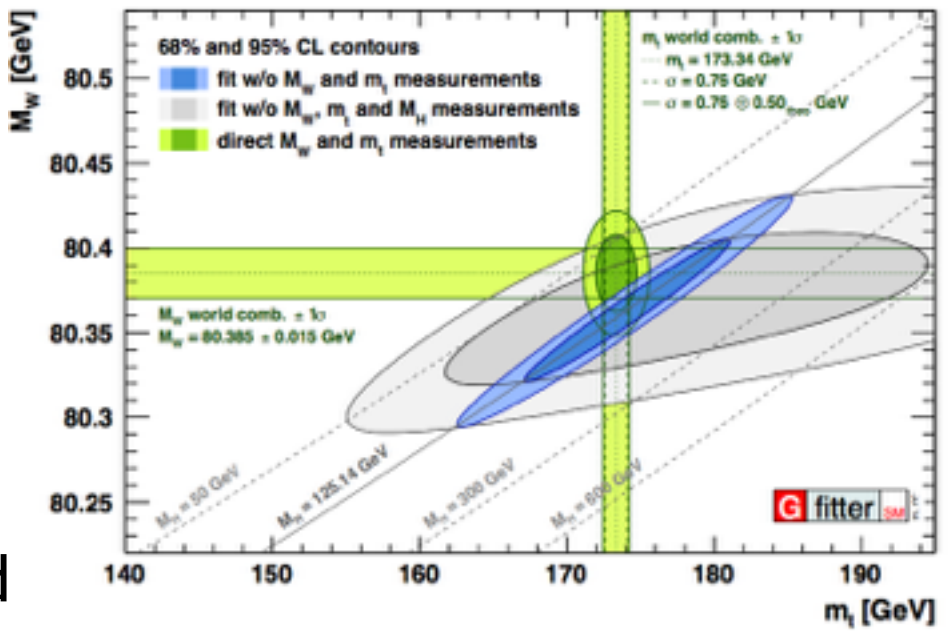

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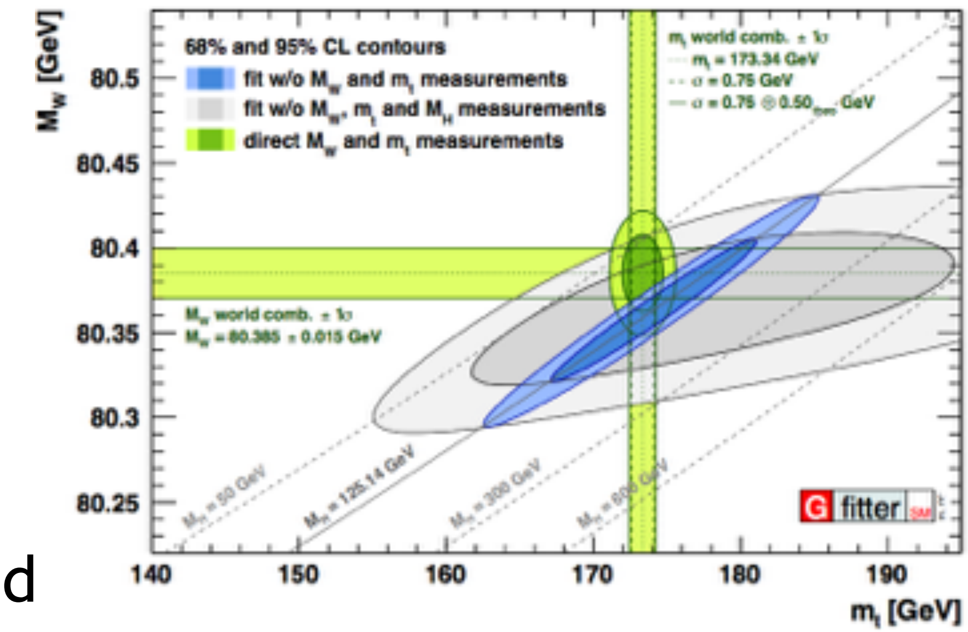
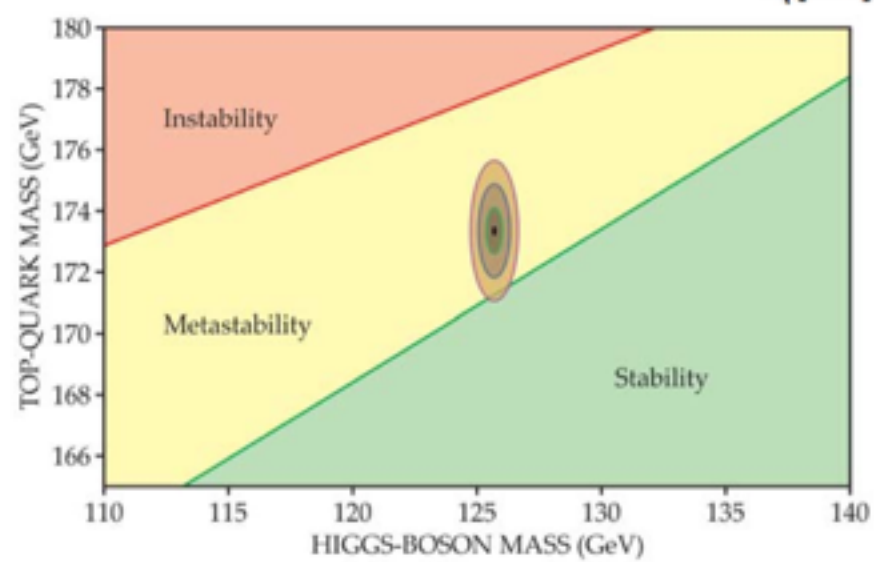
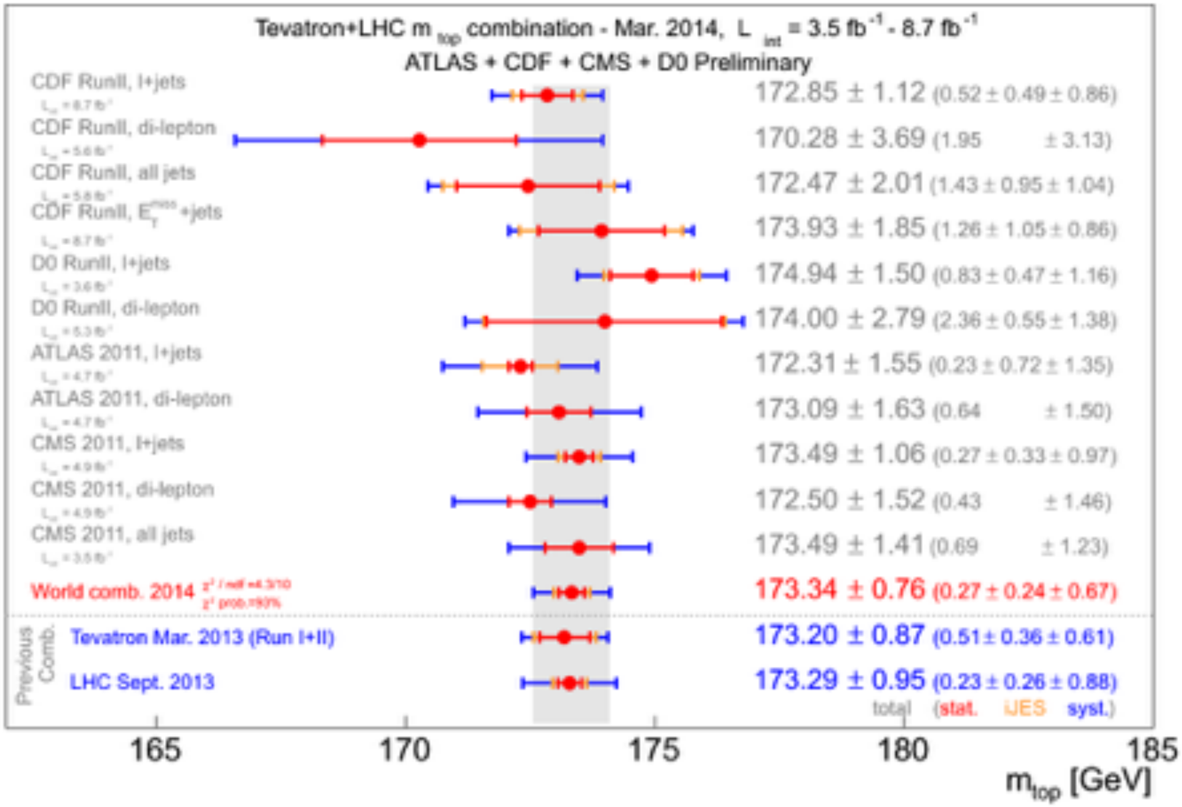
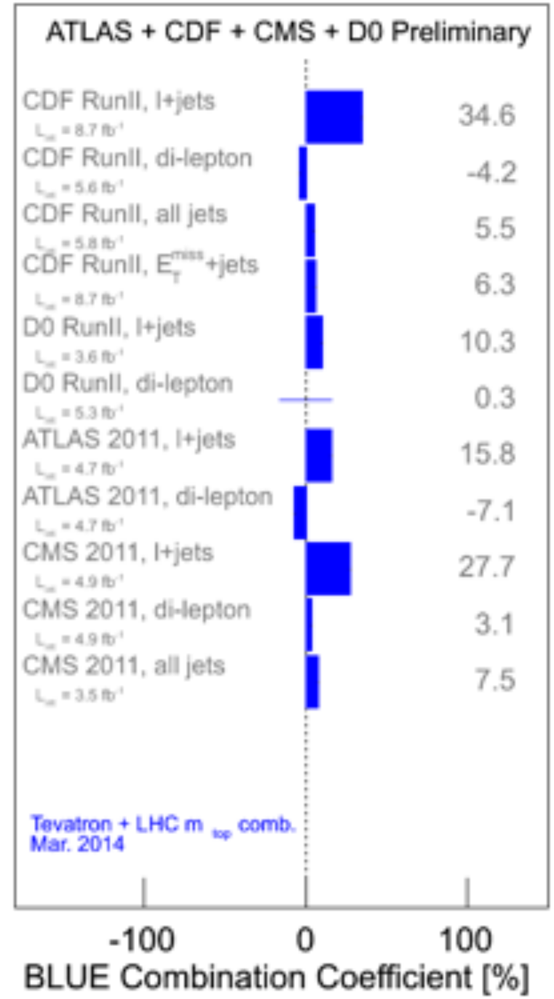
- ✓ If there is new physics related to EWSB, top physics is a place to look for
- ✓ If the SM is assumed valid up to very high scales, the EW vacuum stability depends crucially on the precise top mass value





Status of top mass measurements





0.44% precision

Status of top mass measurements

Results after 2014's World combination

- D0 final measurement in lepton+jets:

  $m_t = 174.98 \pm 0.58_{stat+JES} \pm 0.49_{syst}$ GeV/c^2 = 174.98 ± 0.76 GeV/c^2

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- CMS 7 + 8 TeV measurements in all channels:

  $m_t = 172.35 \pm 0.16_{stat} \pm 0.48_{syst}$ GeV/c^2 (lepton+jets)
  $m_t = 172.32 \pm 0.25_{stat} \pm 0.59_{syst}$ GeV/c^2 (all-jets)
  $m_t = 172.82 \pm 0.19_{stat} \pm 1.22_{syst}$ GeV/c^2 (dilepton)

  $m_t = 172.44 \pm 0.13_{stat} \pm 0.47_{syst}$ GeV/c^2 = 172.44 ± 0.48 GeV/c^2

  0.28% precision!

  PRD **93**, 072004 (2016)

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PRD **93**, 072004 (2016)

>3σ difference

New top mass measurement at CDF

P. Bartos	A. Komenius University, Bratislava
G. Bellettini	University of Pisa & Fermilab
L. A. Jimenez-Rugama	Illinois Institute of Technology
S. Mrenna	Fermilab
I. Suslov	JINR Dubna
C. Tosciri	University of Pisa
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Last top mass measurement from CDF, aiming to:

- ◇ Reach highest possible precision from CDF data
- ◇ Examine tension between “low” LHC and “high” Tevatron results

Definition of top pair candidate event

- ✓ One and only good lepton: central electron / tight or loose muon
- ✓ At least 4 jets, reconstructed with a cone algorithm (JetClu) of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$
- ✓ A number of b-jet tags, varying by candidate event category, using a secondary vertex algorithm (SecVtx)
- ✓ Large missing E_T, reflecting the presence of a neutrino from the leptonic W boson decay in the final state

"Tight" and "loose" event selection

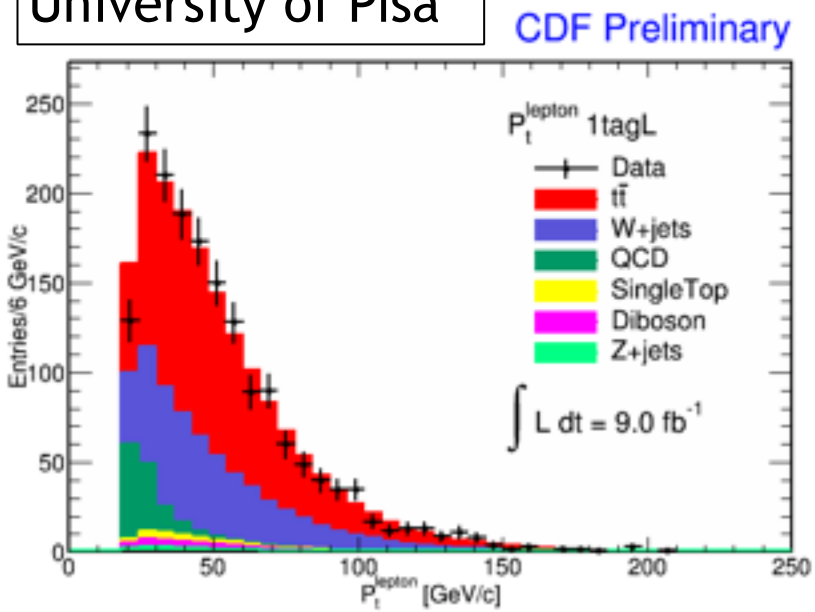
- ✓ Tight jet: $E_T > 20$ GeV, $|\eta| < 2.0$
- ✓ Loose jet: $E_T > 12$ GeV, $|\eta| < 2.4$
- ✓ Tight selection: events with exactly 4 tight jets and any loose jets
- ✓ Loose selection: events with ≥ 3 T jets + ≥ 1 L jet
- ✓ Categories by selection/b-tags: 0-tag, 1-tagL, 1-tagT, 2-tagL, 2-tagT

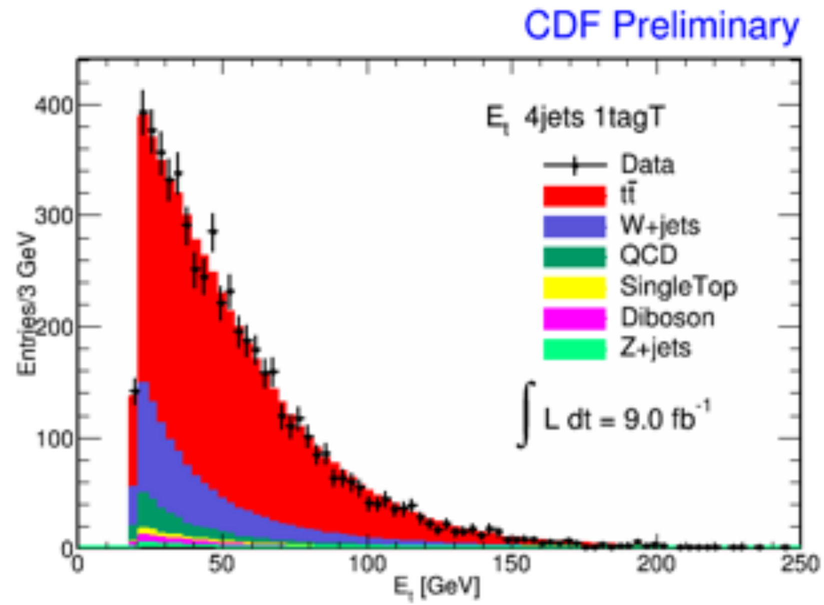
Physics processes and simulation models

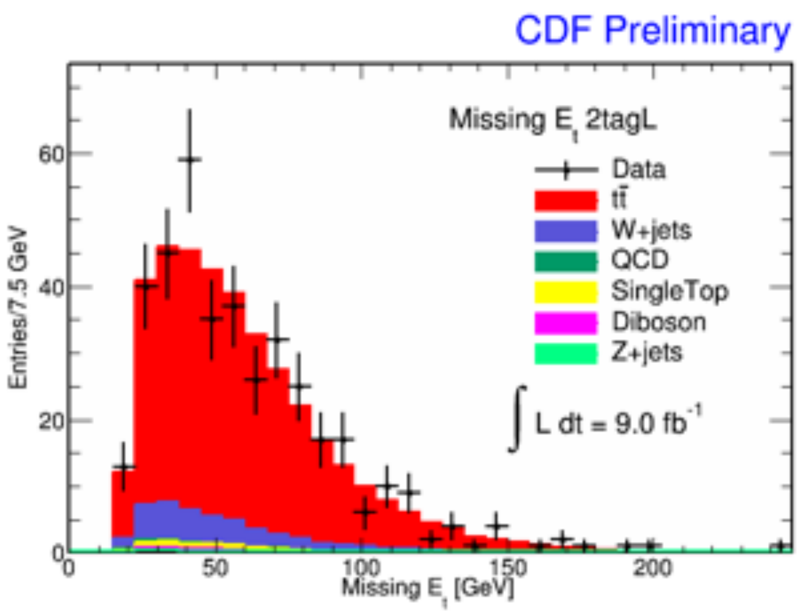
- $t\bar{t}$ signal: Powheg + Pythia, S. Frixione *et al*., JHEP07, 0709 (2007)
- W/Z + jets: Alpgen+Pythia, M.L. Mangano *et al*., JHEP0307:001 (2003)
- Dibosons: Pythia 6, T. Sjöstrand *et al*., JHEP06, 026 (2006)
- Single top: Madgraph 4 + Pythia, J. Alwall *et al*., JHEP09, 028 (2007)
- QCD: data with lepton failing one of the "good lepton" criteria
- All MC samples processed through the standard CDF detector simulation and event reconstruction software, E. Gerchtein and M. Paulini, arXiv:physics/0306031 (2003)

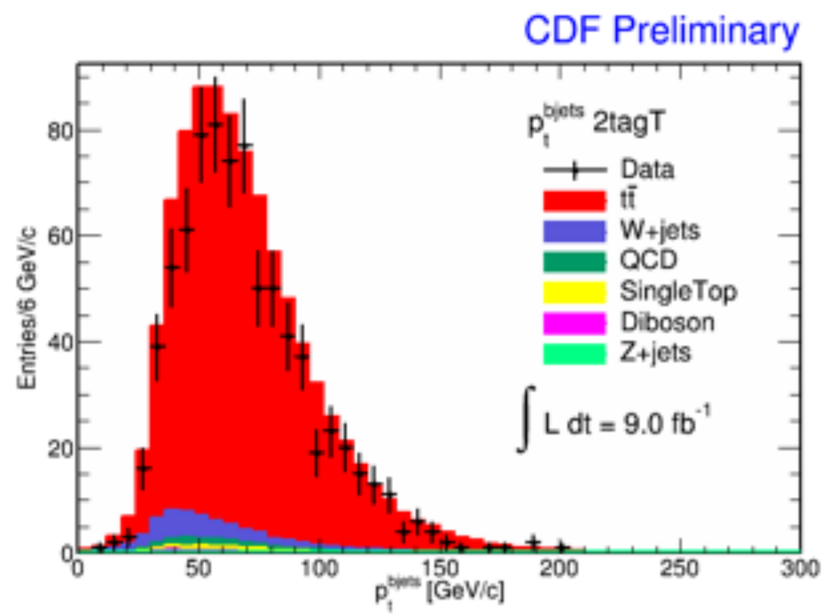
C. Tosciri, Laurea
University of Pisa

Kinematic spectra









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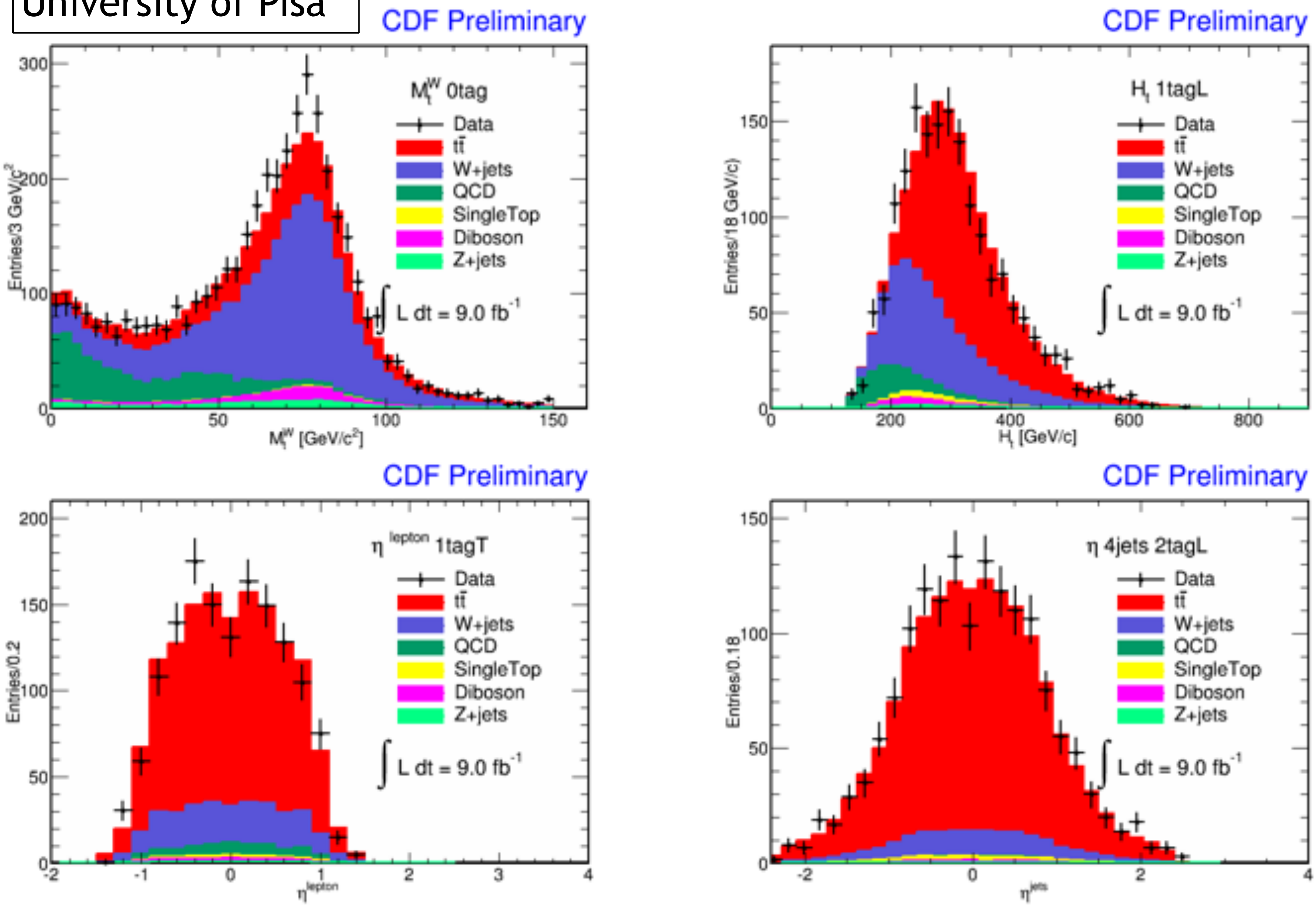

Improvements relative to the previous measurement

- ➢ More luminosity: from 5.6 fb^{-1} to 9 fb^{-1} → 60% more data
- ➢ New candidate categories: 0-tag, 1-tagL, 2-tagL → 30% more candidate events from loose categories
- ➢ New matrix element integration method, allowing for reliable error estimation → higher integration accuracy
- ➢ NLO singal MC: Powheg + Pythia → reduction of uncertainty from higher-order terms

The matrix element method

- ✓ Based on the use of the m_t dependence of the top quark pair production cross section through the maximization of a suitable likelihood function

$$L = \prod_{i=1}^{N} \left(\frac{N_s}{N} L_i^s + \frac{N_b}{N} L_i^b \right)$$

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- ✓ Provides maximal statistical sensitivity by exploiting the full topological and kinematic information of each event
- ✓ Idea conceived already in Tevatron Run I, repeatedly applied by both Tevatron experiments in all top quark pair decay channels and many versions for various measurements
- ✓ Last applied by CDF in lepton+jets using 5.6 fb^{-1}, most precise single m_t measurement at the time, PRL **105**, 252001 (2010)
- ✓ Last applied by D0 in lepton+jets using 9.7 fb^{-1}, most precise single m_t measurement at the time, PRL **113**, 032002 (2014)

In situ JES calibration

Choose a m_t estimator which is also sensitive to m_W, so that a shift of the mass of the hadronically decaying W from the peak due to the JES uncertainty induces a large change of the estimator

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$$L_i^s\left(m_t, \Delta_{JES}\right) \propto P\left(\vec{x}_i \middle| m_t, \Delta_{JES}\right)$$

$$JES = \frac{p_T^{Calor-jet}}{p_T^{MC-jet}} = 1 + \Delta_{JES}\sigma_{JES}\left(\vec{p}^{\,jet}\right)$$

- ❑ Define the likelihood as a 2-variable function of m_t and Δ_{JES}
- ❑ Δ_{JES}=0 defines the nominal JES
- ❑ $P(x_i|m_t,\Delta_{JES})$ strongly dependent on m_W and maximal at the m_W peak

Definition of the likelihood

$$L_i^s\left(m_t,\Delta_{JES}\right)=\frac{1}{N\left(m_t\right)}\frac{1}{A\left(m_t,\Delta_{JES}\right)}\sum_{j=1}^{24}w_{ij}P\left(\vec{x}_i\middle|m_t,\Delta_{JES}\right)$$

Event likelihood

Cross section

Acceptance

Event probability

Definition of the likelihood

$$L_i^s(m_t,\Delta_{JES}) = \frac{1}{N(m_t)}\frac{1}{A(m_t,\Delta_{JES})}\sum_{j=1}^{24} w_{ij} P(\vec{x}_i | m_t,\Delta_{JES})$$

$$P(\vec{x}|m_t,\Delta_{JES}) = \int T(\vec{x}|\vec{y},\Delta_{JES}) \left| M^{t\bar{t}}_{2p\rightarrow l\nu_l+4p}(m_t,\vec{y}) \right|^2 \times \frac{f(z_1,Q^2) f(z_2,Q^2)}{z_1 z_2}\Big|_{Q=2m_t} dz_1 dz_2 d\Phi(\vec{y})$$

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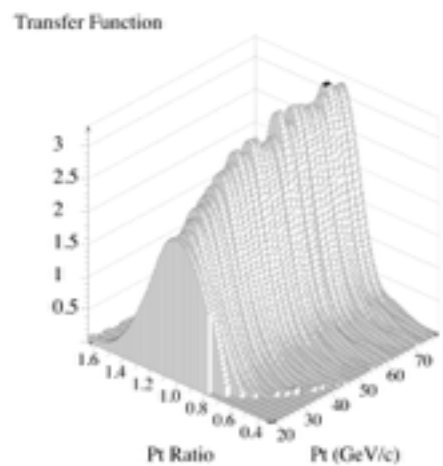
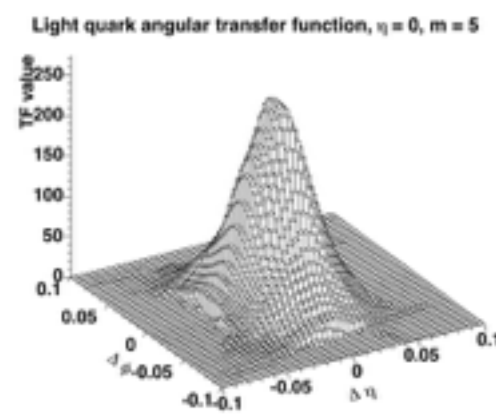
From MC, separately for b & light jets

$$T = F_1\left(\frac{p_T^j}{p_T^p}, p_T^p, \eta_p, m\right) \times F_2\left(\Delta\eta_{j-p}, \Delta\phi_{j-p}, p_T^p, \eta_p, m\right)$$





PRL **105**, 252001 (2010)

Method calibration

- Use joint signal+background $L(m_t,\Delta_{JES})$ in pseudo-experiments (PEs)
- Run PEs with Poisson average equal to the expected candidate events
- Find average m_t, bias, expected σ_m, pull width for the PE ensemble
- Correct for any bias in m_t and σ_m ; apply similar procedure for Δ_{JES}
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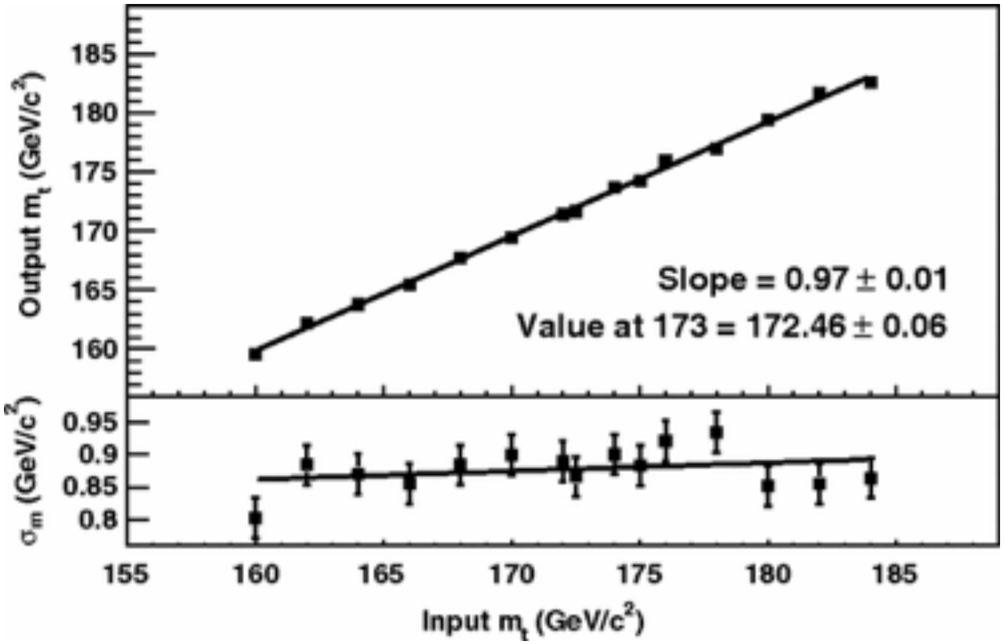

From PRL **105**, 252001

Systematic uncertainties

Systematic source	Uncertainty (GeV/
Calibration	*0.10*
MC generator	*0.37*
Initial/final state	*0.15*
Residual JES	*0.49*
b-JES	*0.26*
Lepton p_T	*0.14*
Multiple collisions	*0.10*
PDF	*0.14*
Background	*0.33*
Color reconnection	*0.37*
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Remove overlap from hadronization (MC generator, Residual JES)

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Remove overlap from hadronization (MC generator, Residual JES)

Reduce by using a background $\mathcal{L}$ (Background)

Remove by using new signal MC (Color reconnection)

Summary

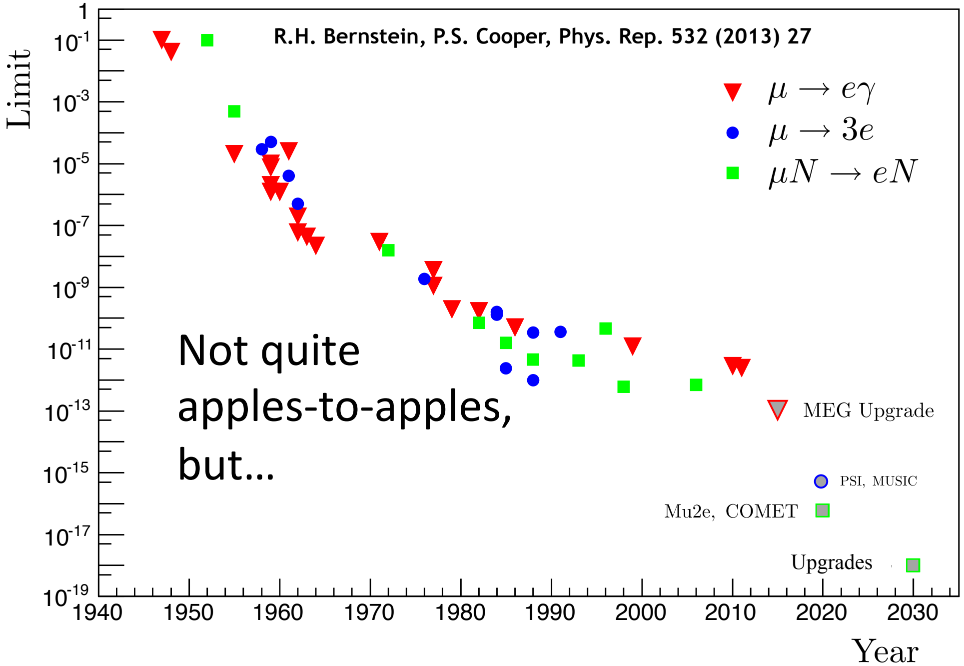
- CDF top program concludes with a high precision measurement
- Using full sample (9 fb^{-1}) & matrix element (optimal) technique
- Revisiting dominant systematic uncertainties
- Last word, most precise top mass result from CDF
- Expected to be included in next World average

The Mu2e experiment at Fermilab: Search for neutrinoless muon-to-electron conversion

Charged lepton flavor violation

- While flavor mixing is observed in the quark and neutrino sectors, Charged Lepton Flavor Violation (CLFV) has never so far been observed
- CLFV is a nearly universal feature of Standard Model extensions
- CLFV is a powerful probe of multi-TeV scale dynamics: complementary to direct collider searches
- Among various possible CLFV modes to search for, rare muon processes offer best combination of new physics reach and experimental sensitivity

History of CLFV searches with μ



Best 90% C.L. limits

- $R_{\mu e} < 7 \times 10^{-13}$ (Sindrum-II 2006)
- $Br(\mu \to e\gamma) < 4.2 \times 10^{-13}$ (MEG 2016)
- $Br(\mu \to 3e) < 1 \times 10^{-12}$ (Sindrum-I 1988)

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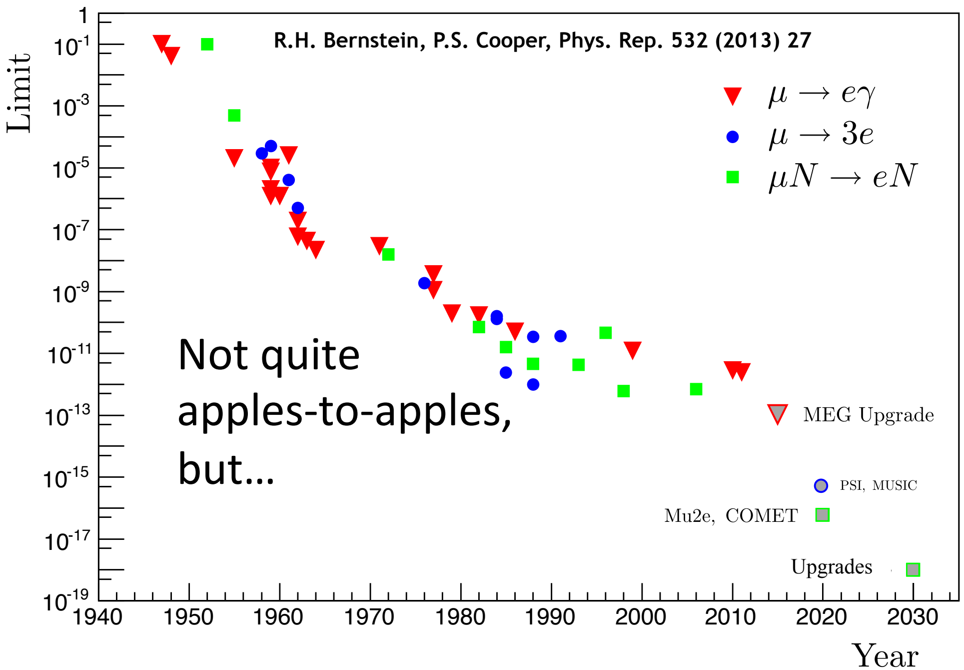

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Mu2e will measure:

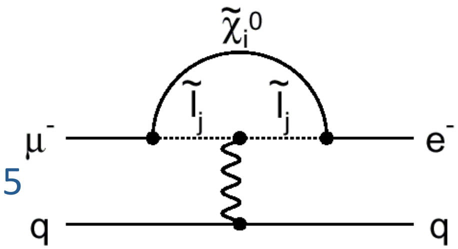
$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- N(A,Z) \to e^- + N(A,Z)\right)}{\Gamma\left(\mu^- N(A,Z) \to \nu_\mu + N'(A,Z-1)\right)}$$

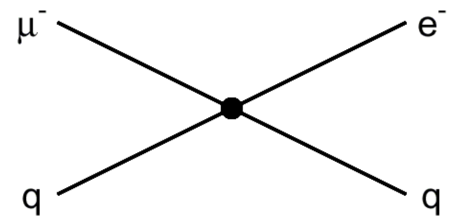
Goal: single event sensitivity of $R_{\mu e}$ = "a few" x 10^{-17}

*Example sensitivities of μ+N → e+N

Supersymmetry

Predictions at 10^{-15}



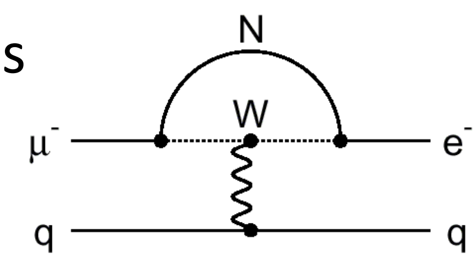


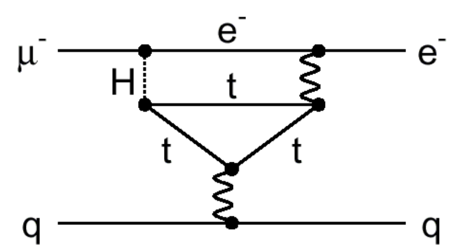
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2 = 8 \times 10^{-13}$



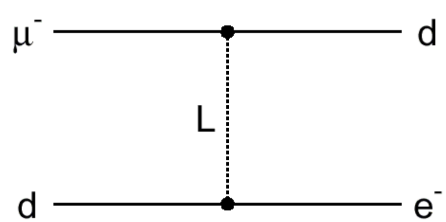


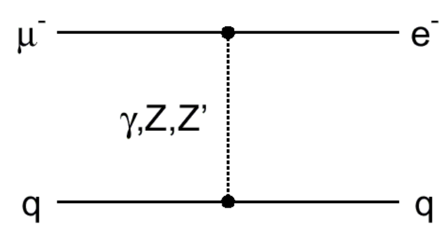
Second Higgs doublet

$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L = 3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/c^2





Heavy Z', Anomalous Z coupling

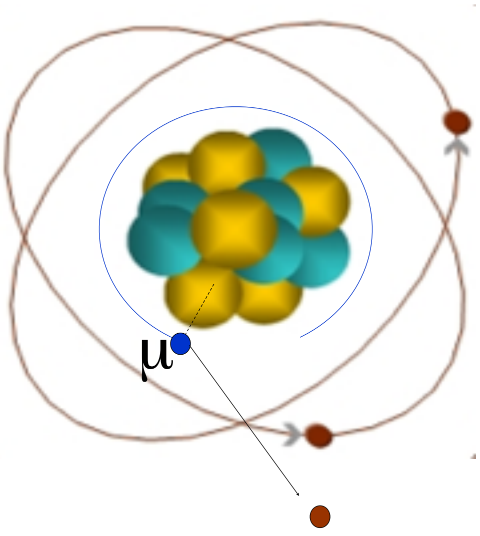
$M_{Z'} = 3000$ TeV/c^2

$B(Z \to \mu e) < 10^{-17}$

*After W. Marciano

Experimental signature of μ+N → e+N

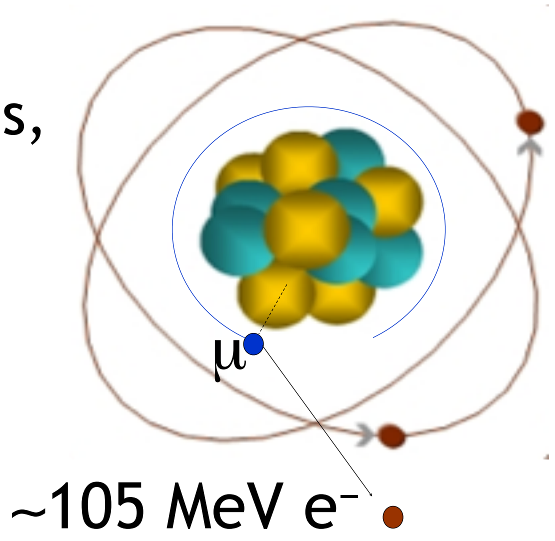
◇ A muon captured by a nucleus has an enhanced probability of decay by the exchange of a virtual particle with the nucleus



Experimental signature of μ+N → e+N

- A muon captured by a nucleus has an enhanced probability of decay by the exchange of a virtual particle with the nucleus
- This reaction recoils against the entire nucleus, producing a *mono-energetic* electron carrying most of the muon rest energy

$$E_e = m_\mu c^2 - \frac{(m_e c^2)^2}{2 m_N c^2}$$



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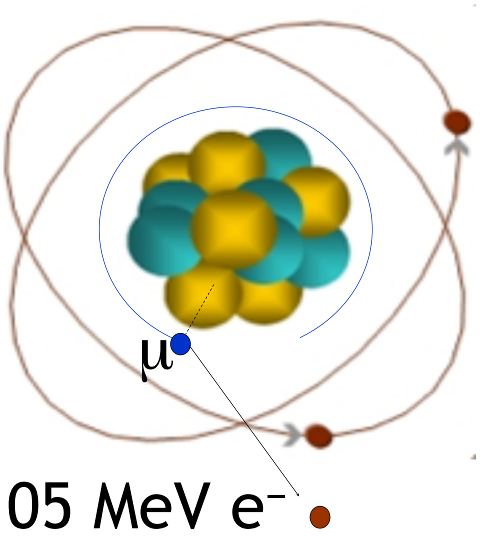

- Similar to $\mu \rightarrow e\gamma$, with important advantages:
  - ✓ No combinatorial background
  - ✓ Because the virtual particle can be a photon *or* heavy neutral boson, this reaction is sensitive to a broader range of new physics

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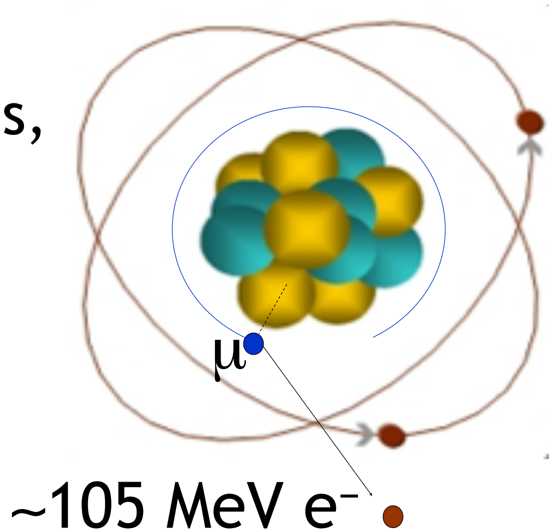
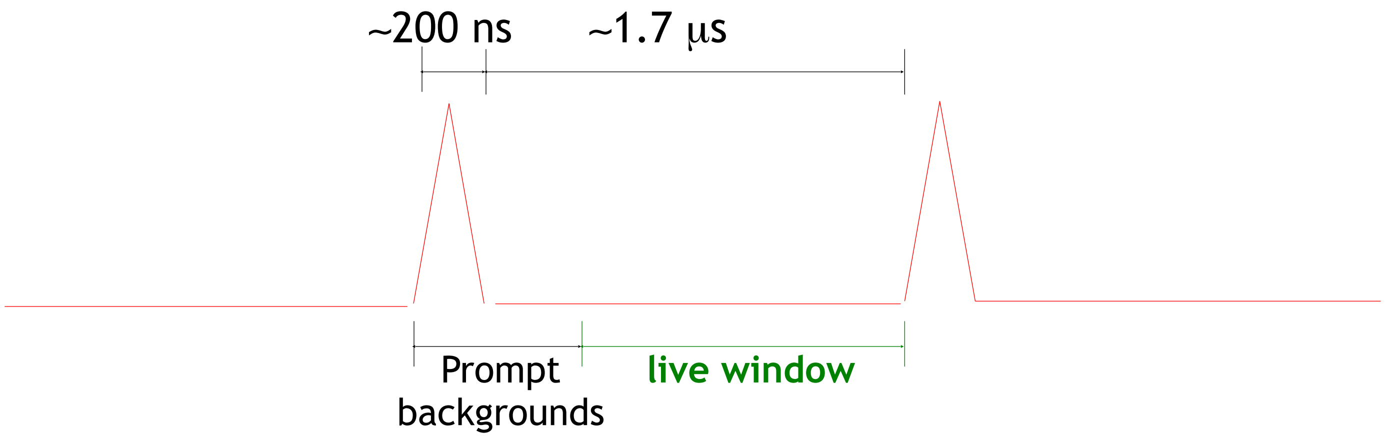


- Similar to $\mu \to e\gamma$, with important advantages:
  - ✓ No combinatorial background
  - ✓ Because the virtual particle can be a photon *or* heavy neutral boson, this reaction is sensitive to a broader range of new physics
- The relative rate of $\mu \to e\gamma$ and $\mu N \to eN$ is the most important clue regarding the details of the physics

Mu2e experimental technique

- ➢ Eliminate prompt beam backgrounds by using a primary beam consisting of short proton pulses with separation on the order of a muon life time



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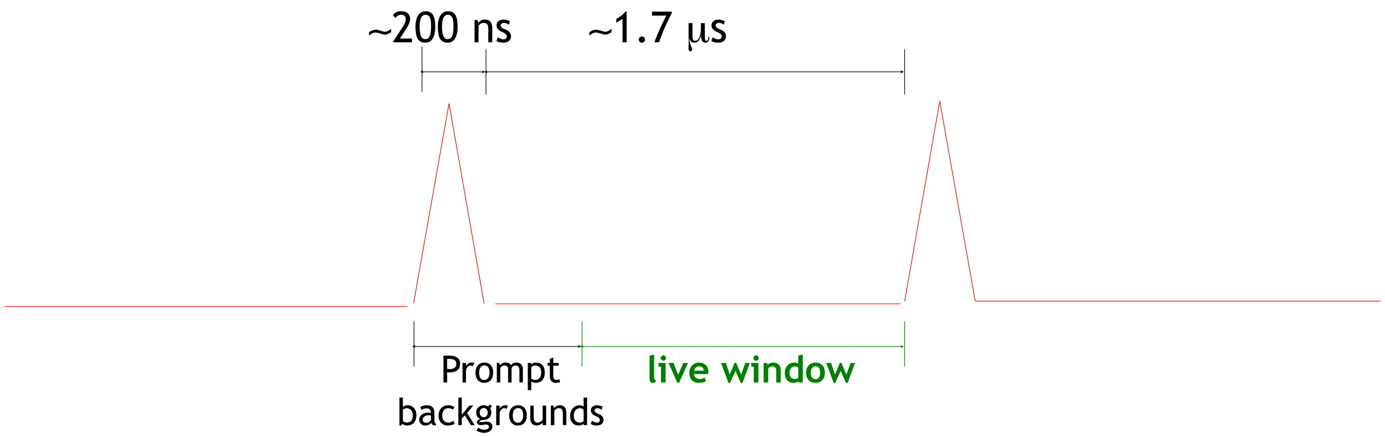

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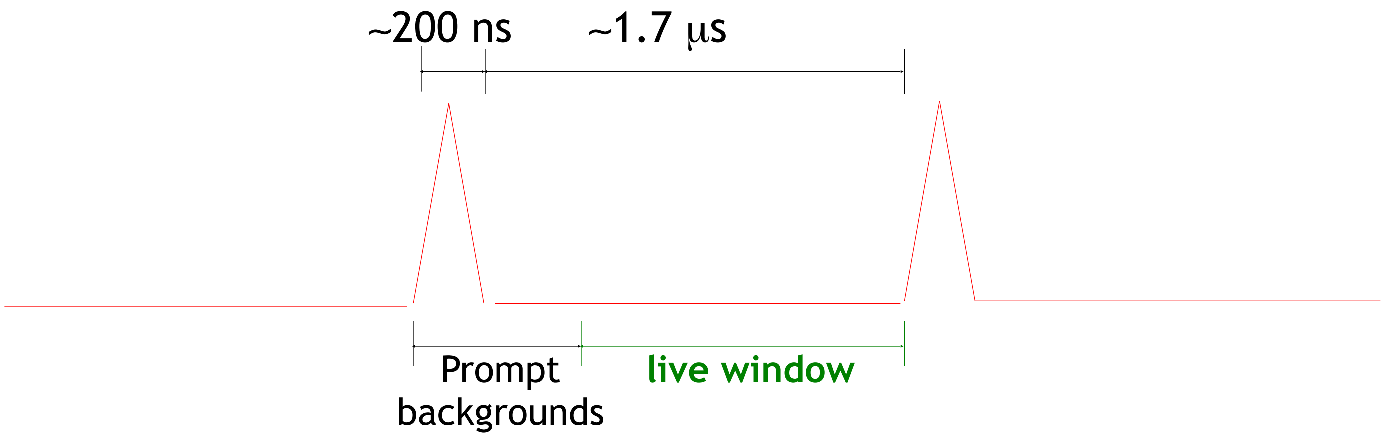
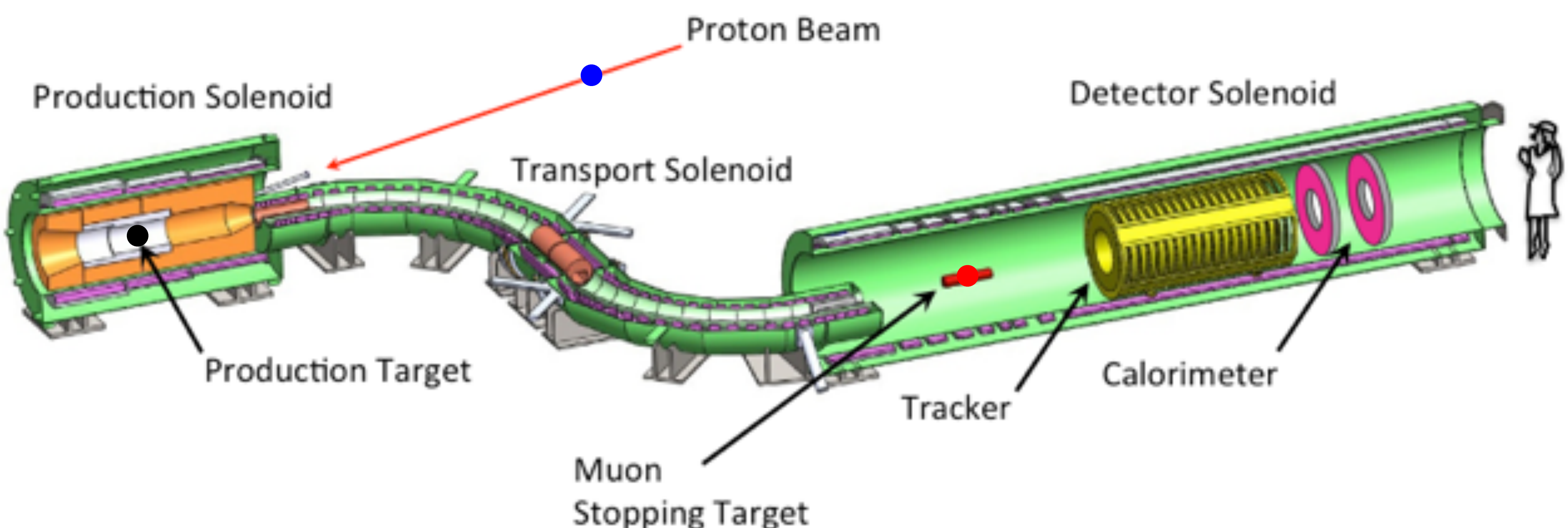


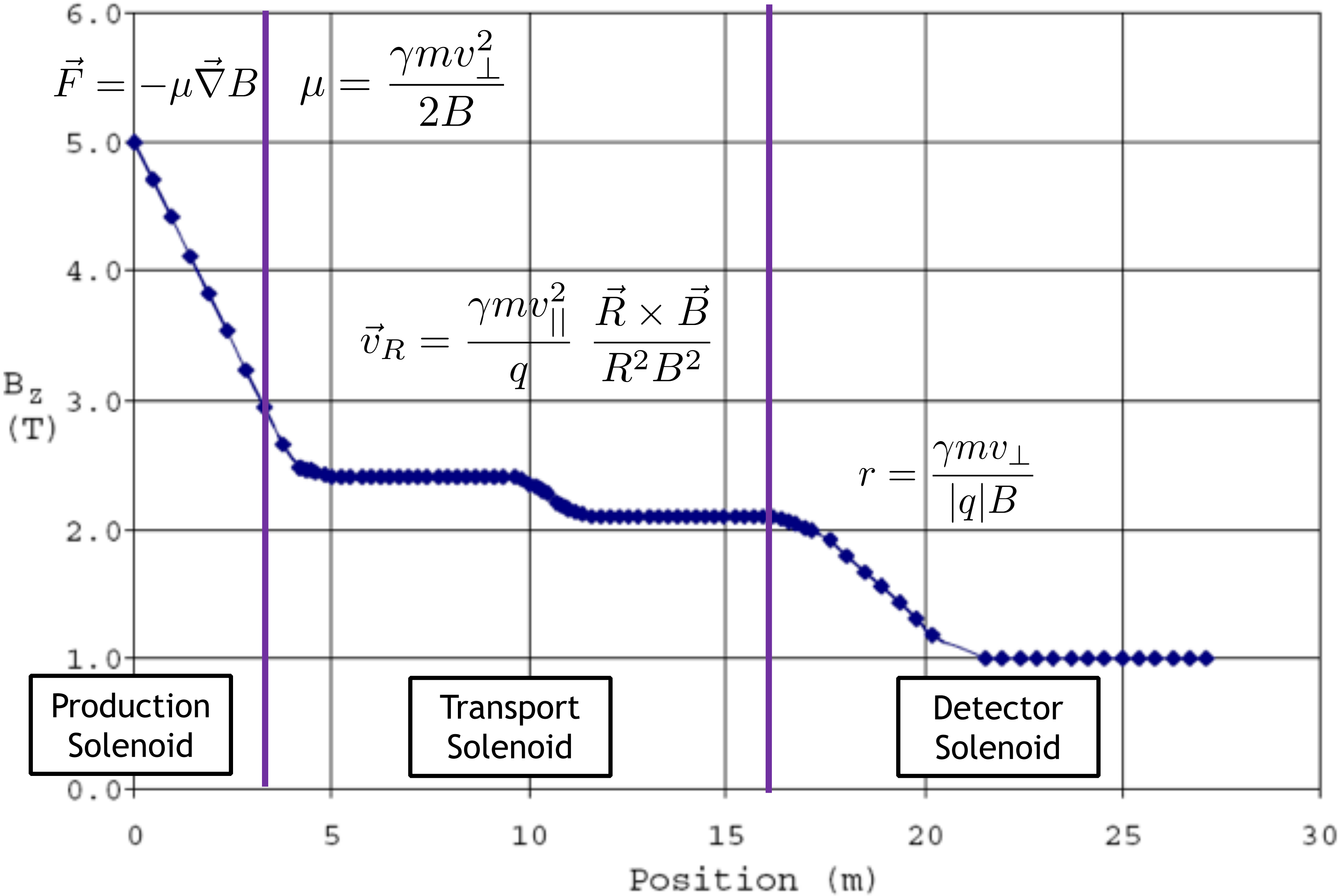
- Design a transport channel to optimize the transport of right-sign, low momentum muons from the production target to the muon capture target
- Design a detector which is very insensitive to electrons from ordinary muon decays

Muon beamline and Mu2e detector



- Production Target
  - ✓ Proton beam strikes target, producing mostly pions
- Production Solenoid
  - ✓ Contains backward pions/muons and reflects slow forward pions/muons
- Transport Solenoid
  - ✓ Selects low momentum, negative muons
- Capture Target, Detector, and Detector Solenoid
  - ✓ Capture muons on Aluminum target and wait for them to decay
  - ✓ Detector blind to ordinary (Michel) decays, with $E \leq \frac{1}{2} m_\mu c^2$
  - ✓ Optimized for $E \sim m_\mu c^2$

Magnetic field



Field testing

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- ➢ Toolkit for field map validation developed (F. Bradascio)
  - ✓ Variety of 3D interpolation algorithms for precision tests
  - ✓ Plotting package for field and gradient plots
  - ✓ Analysis package mapping differences on the experiment geometry and scanning their importance

Implications of field uncertainties (from coil misalignments)

- Stopping rates:
  - ✓ Uncertain μ^- flux on capture target
  - ✓ Uncertain π^- flux on capture target (background)

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Studied with misaligned coil simulations

F. Bradascio, University of Pisa (Laurea 07/22/16)

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F. Bradascio, Laurea University of Pisa

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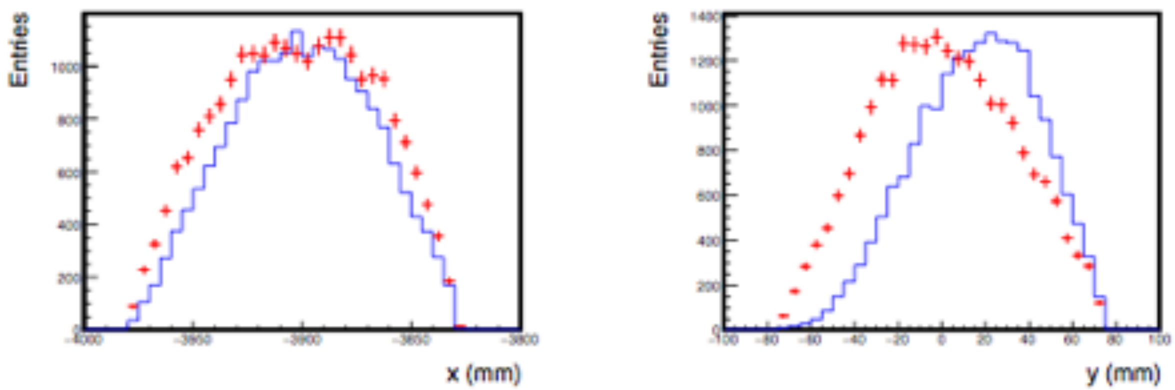
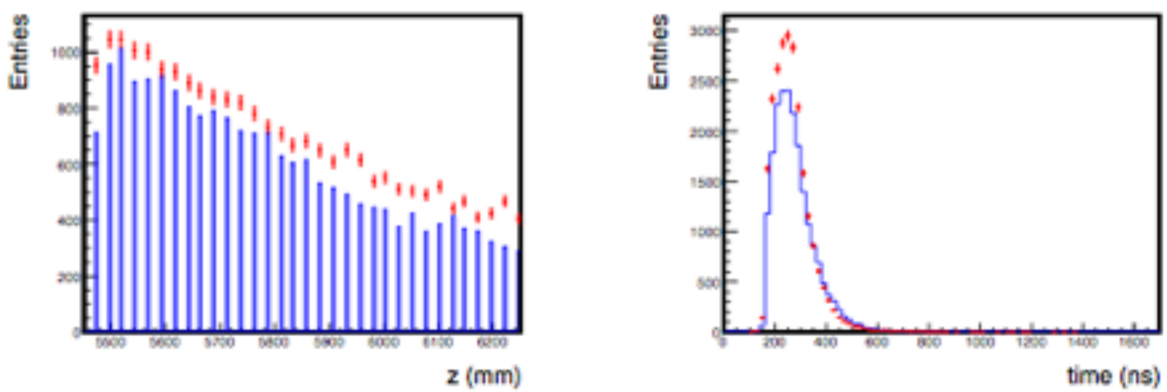


Stopped π^- distributions for exaggerated misalignment (blue histograms)



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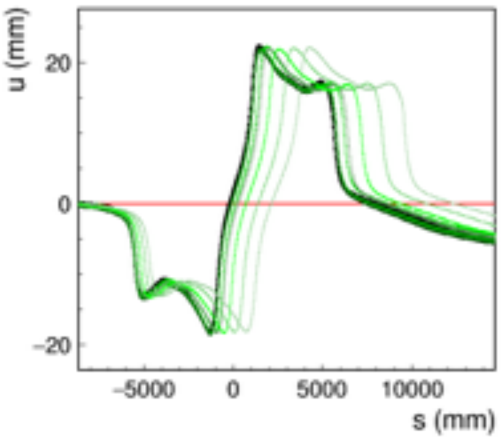

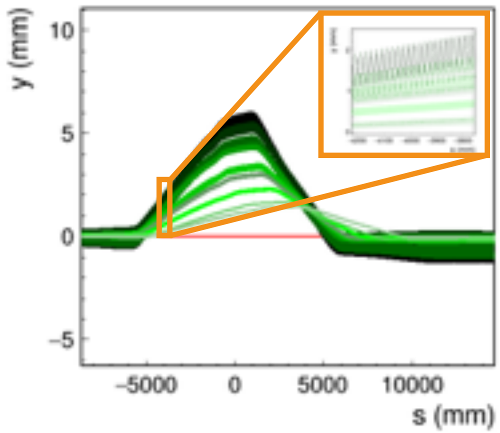

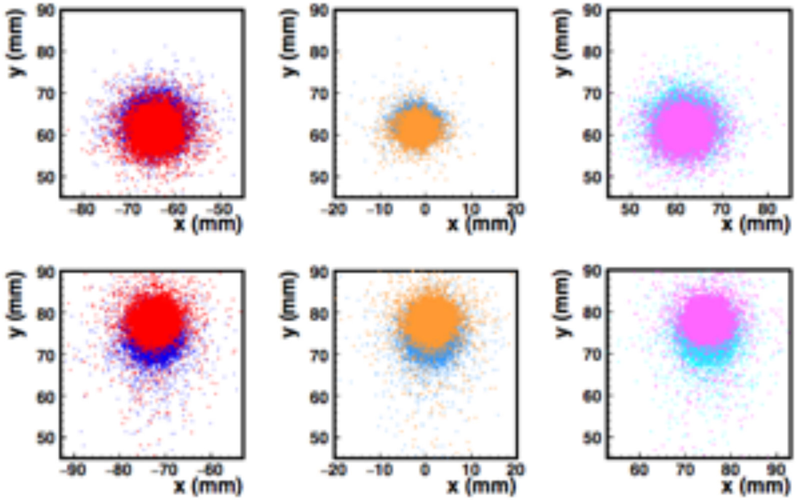

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F. Bradascio, Laurea
University of Pisa

Summary

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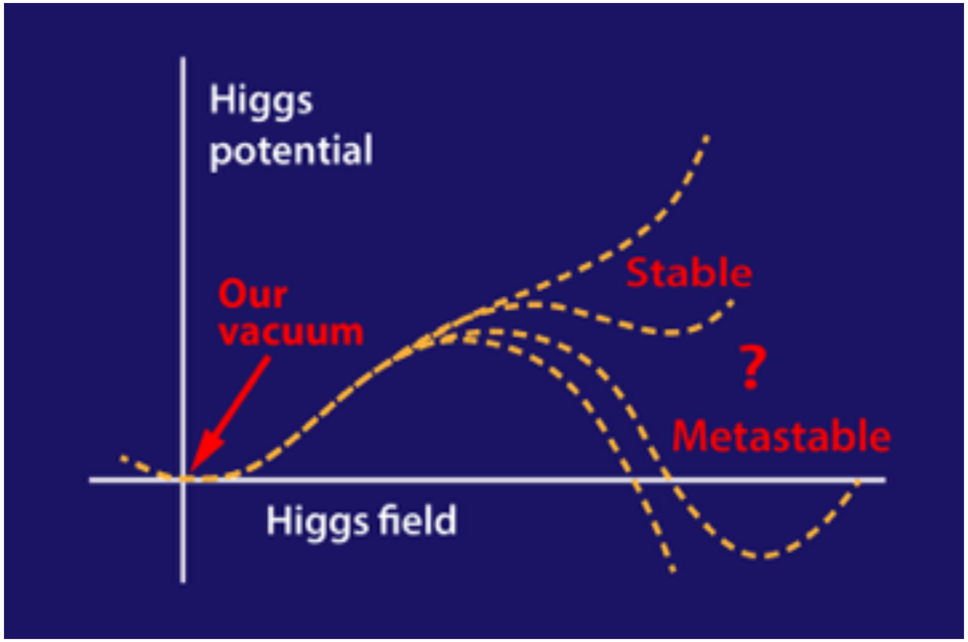
- Field studies have shown that the design operating point is stable, by demonstrating that relevant physics quantities (stopping rates, background expectations) are insensitive to field uncertainties from realistic solenoid misalignments

Top mass backup

Stability of the Higgs potential



- Interplay of the Higgs field mass and self-coupling terms shapes the Higgs potential
- For some Higgs and top mass values, the Higgs potential can go negative at very short distances, allowing tunneling to a lower-energy state than the present minimum (vacuum)
- Metastability scenarios are related to inflation

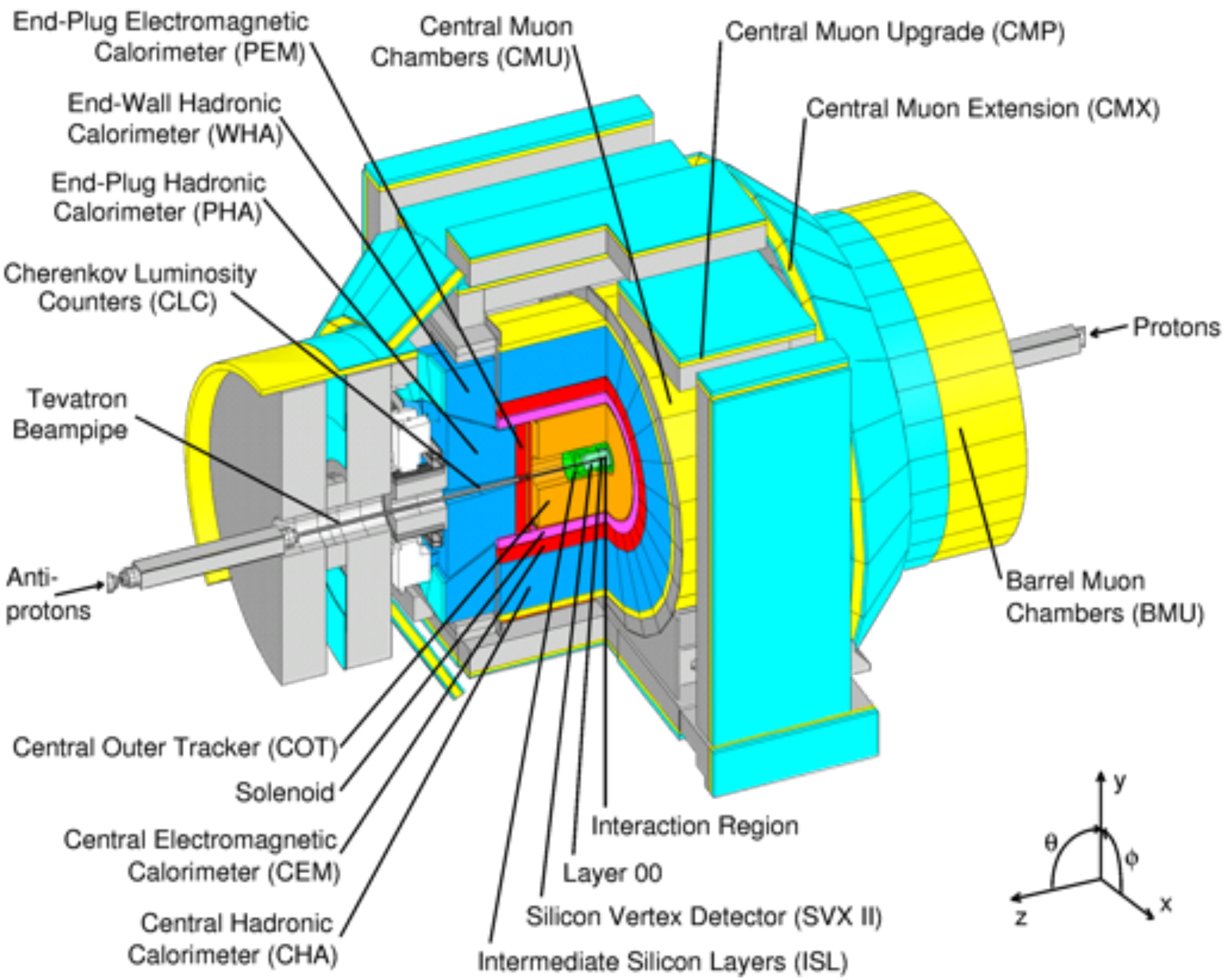
The Tevatron

Proton-antiproton collider operating at a collision energy of 1.8 TeV in 1992-96 (Run I) and 1.96 TeV in 2001-11 (Run II)

World's highest-energy collider until 2010

- ✓ Located at Fermilab near Chicago
- ✓ 1 km radius
- ✓ 1976: Construction started
- ✓ 1985: Commissioning
- ✓ 1987: CDF Run 0
- ✓ Continuous upgrades over 25 years of operations

The Collider Detector at Fermilab (CDF)



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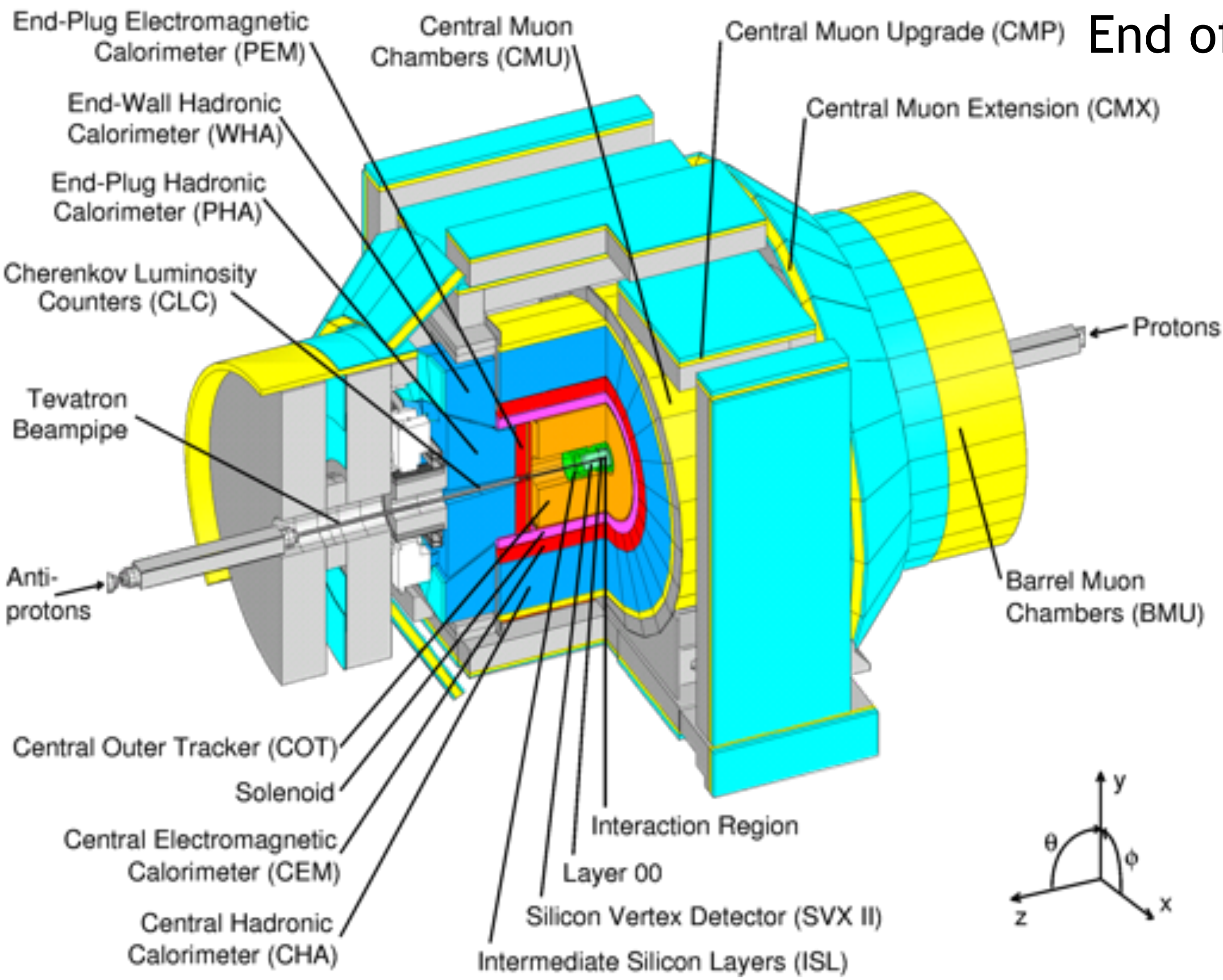
First CDF $p\bar{p}$ event: 1985
End of operations: 2011



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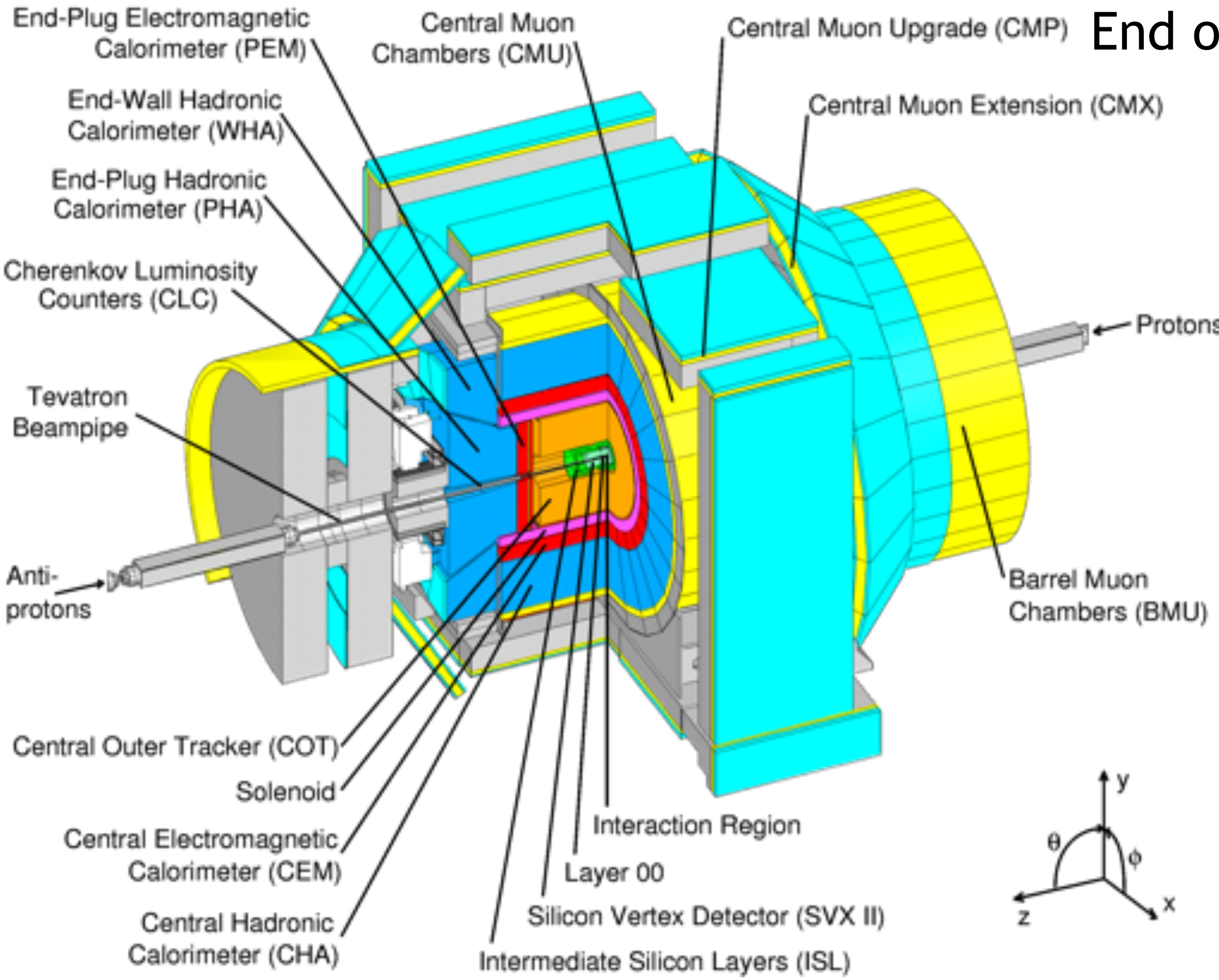

Lepton coverage:
$|\eta| < 2.0$ (e)
$|\eta| < 1.5$ (μ)

Jets to $|\eta| < 2.8$

b-tagging with $|\eta| < 1.5$

Selection criteria of top pair candidate events

	0-tag	1-tagL	1-tagT	2-tagL	2-tagT
Lepton p_T (GeV)	> 20	> 20	> 20	> 20	> 20
Lepton $\|\eta\|$	< 1	< 1	< 1	< 1	< 1
1st 3 jets E_T (GeV)	> 20	> 20	> 20	> 20	> 20
1st 3 jets $\|\eta\|$	< 2	< 2	< 2	< 2	< 2
4th jet E_T (GeV)	> 20	> 12	> 20	> 12	> 20
4th jet $\|\eta\|$	< 2	< 2.4	< 2	< 2.4	< 2
Extra jets	$E_T < 20$	Any L ≥ 1 T	Any L	Any L ≥ 1 T	Any L
b-tags ($\|\eta\|$<1.5)	0	1	1	> 1	> 1
Missing E_T (GeV)	> 20	> 20	> 20	> 20	> 20
$\Delta\varphi(\not{E}_T$,jet) (rad)	> 0.5	> 0.5	> 0.5	Any	Any

Estimated sample composition at 9 fb^{-1} luminosity

	0-tag	1-tagL	1-tagT	2-tagL	2-tagT	All
W + h.f.	*697*	*357*	*161*	*34*	*21*	*1269*
W + l.f.	*1581*	*171*	*77*	*3*	*2*	*1834*
Z + jets	*169*	*25*	*14*	*2*	*1*	*212*
Dibosons	*166*	*31*	*18*	*3*	*2*	*220*
Single top	*14*	*17*	*8*	*7*	*5*	*50*
QCD	*623*	*120*	*60*	*1*	*6*	*811*
Background	*3251*	*720*	*338*	*49*	*37*	*4395*
Signal	*960*	*999*	*1086*	*331*	*425*	*3801*
Total	*4211*	*1719*	*1424*	*380*	*462*	*8196*
S/B	*0.3*	*1.4*	*3.2*	*6.8*	*10.6*	*0.9*
Observed	*4474*	*1711*	*1434*	*365*	*375*	*8359*

Definition of the likelihood

$$N(m_t) = \int |M|^2 \frac{f(z_1) f(z_2)}{z_1 z_2} dz_1\, dz_2\, d\Phi(\vec{y})$$

w_{ij} = permutation weight depending on # of b-tags

$$L_i^s(m_t, \Delta_{JES}) = \frac{1}{N(m_t)} \frac{1}{A(m_t, \Delta_{JES})} \sum_{j=1}^{24} w_{ij} P(\vec{x}_i | m_t, \Delta_{JES})$$

$$A = \frac{N_{sel}(m_t, \Delta_{JES})}{N_{tot}(m_t)}$$

$$P(\vec{x} | m_t, \Delta_{JES}) = \int T(\vec{x} | \vec{y}, \Delta_{JES}) \left| M^{t\bar{t}}_{2p \to l\nu_l + 4p}(m_t, \vec{y}) \right|^2 \times \frac{f(z_1, Q^2) f(z_2, Q^2)}{z_1 z_2} \bigg|_{Q = 2m_t} dz_1 dz_2 d\Phi(\vec{y})$$

$$\int T(\vec{x} | \vec{y}, \Delta_{JES}) d^3x = \varepsilon(\vec{y})$$

$$d\Phi(\vec{y}) = \prod_{k=1}^{6} \frac{d^3 y_k}{(2\pi)^3 2E_k}$$

Integration elements

- $M^{t\bar{t}}_{2p\to l\nu_l+4p}$: Kleiss-Stirling LO ME, including qq, gg, & spin correlations, R. Kleiss and W. J. Stirling, Z. Phys. **40**, 419 (1988)
- $M^{W}_{2p\to l\nu_l+4p}$: Madgraph5 W + 4 partons ME, J. Alwall *et al.*, JHEP07, 079 (2014)
- f : CTEQ5L, H. L. Lai *et al.*, Eur. Phys. J. C **12**, 375 (2000)
- $T = F_1\left(\frac{p_T^j}{p_T^p}, p_T^p, \eta_p, m\right) F_2\left(\Delta\eta_{j-p}, \Delta\phi_{j-p}, p_T^p, \eta_p, m\right)$: From MC, separately for b & light jets
- Integration variables: $2\times\left\{m_t^2, m_W^2\right\}, \log\left(p_1/p_2\right)_{W\to j_1 j_2}, \vec{p}_T^{\,t\bar{t}}, 4\times\left\{\eta,\phi,m\right\}_p$
- Quasi-MC integration, F. J. Hickernell and L. A. JimenezRugama, arXiv:1410.8615: 18 variables integrated using importance sampling, m_W^2 integrated with a grid-based procedure because of phase space singularities when $\partial m_W^2 / \partial p_z^\nu = 0$

Mu2e backup

Significance

➢ Backgrounds

Category	Background process		Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)		0.199±0.092
	Muon radiative capture (RMC)		$0.000^{+0.004}_{-0.000}$
Late arriving	Pion radiative capture (RPC)		0.023±0.006
	Muon decay-in-flight (μ-DIF)		<0.003
	Pion decay-in-flight (π-DIF)		0.001±0.001
	Beam electrons		0.003±0.001
Miscellaneous	Antiproton induced		0.047±0.024
	Cosmic ray induced		0.096±0.020
		Total	0.37±0.10

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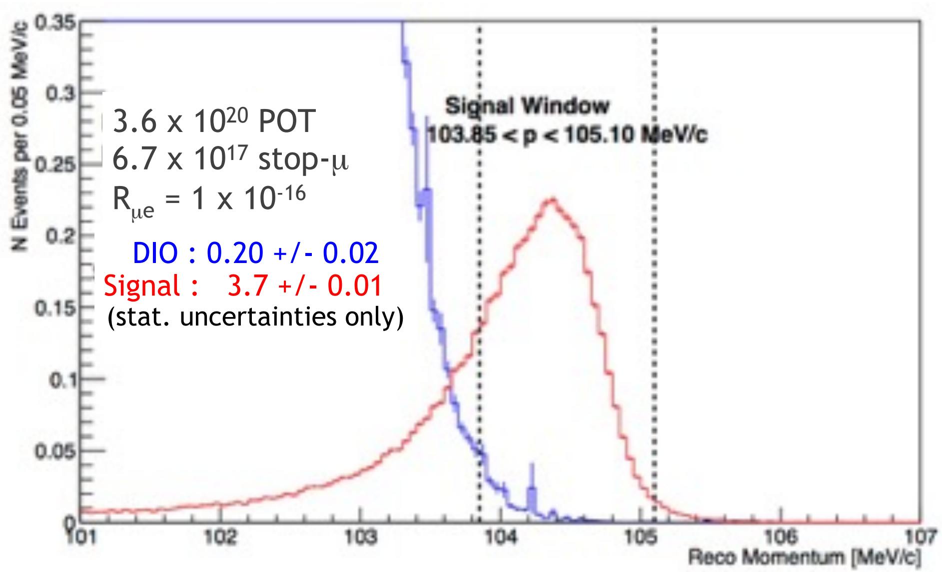
4 orders of magnitude improvement!

Sensitivity

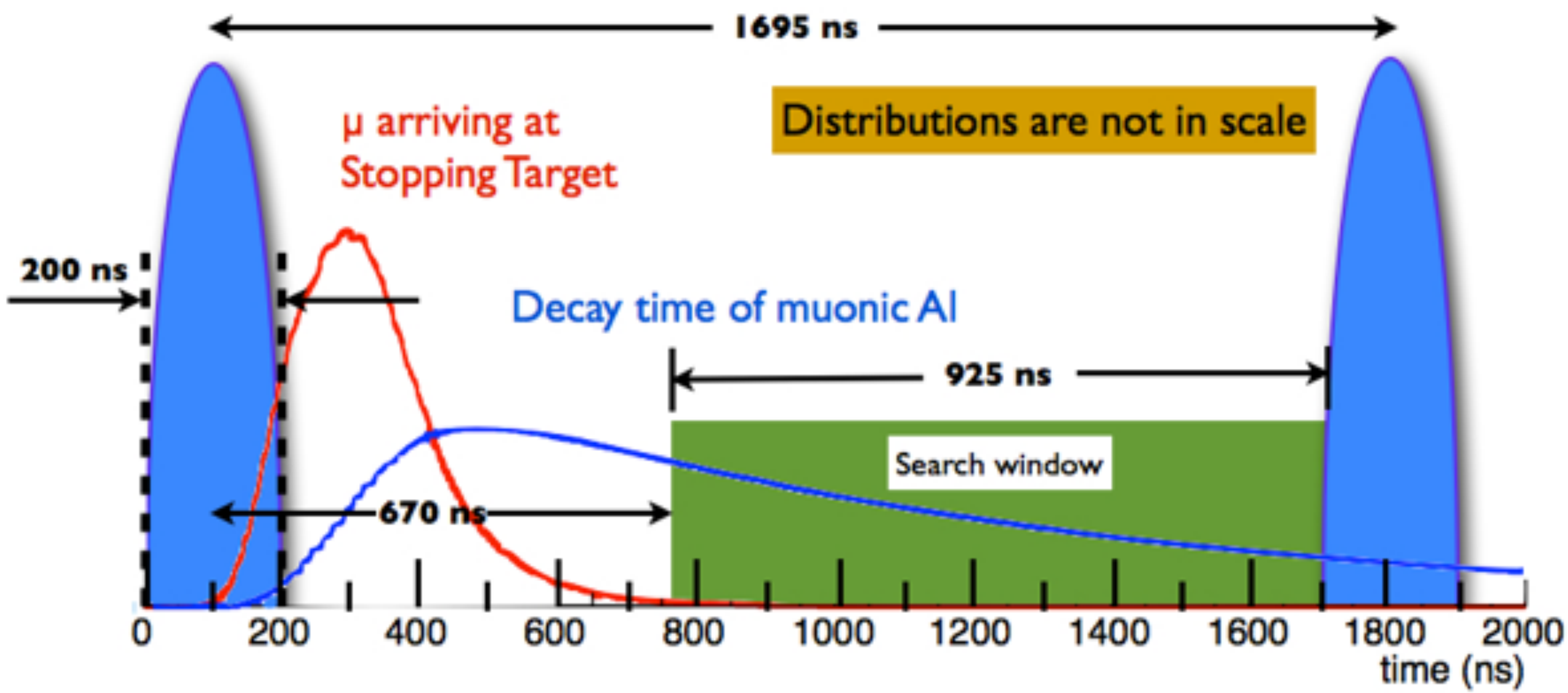
- Cuts chosen to maximize significance
- 3.6×10^{20} protons on target
  - ✓ 3 years nominal running



Parameter	Value
Running time @ 2×10^{7} s/yr.	3 years
Protons on target per year	1.2×10^{20}
μ^- stops in stopping target per proton on target	0.0016
μ^- capture probability	0.609
Fraction of muon captures in live time window	0.51
Electron Trigger, Selection, and Fitting Efficiency in Live Window	0.10

Single Event Sensitivity: $R_{\mu e} = 3 \times 10^{-17}$

Event time structure



- μ^- are accompanied by e^-, π^-, …
- Extinction system makes prompt background ~equal to all other backgrounds
  - ✓ 1 out of time proton per 10^{10} in time protons
- Lifetime of muonic Al: 864 ns

Mu2e (MELC) experimental technique

- Determining the Z dependence is very important, but
- Lifetime is *shorter* for high-Z
  - ✓ Decreases useful live window
- Also, need to avoid background from radiative muon capture

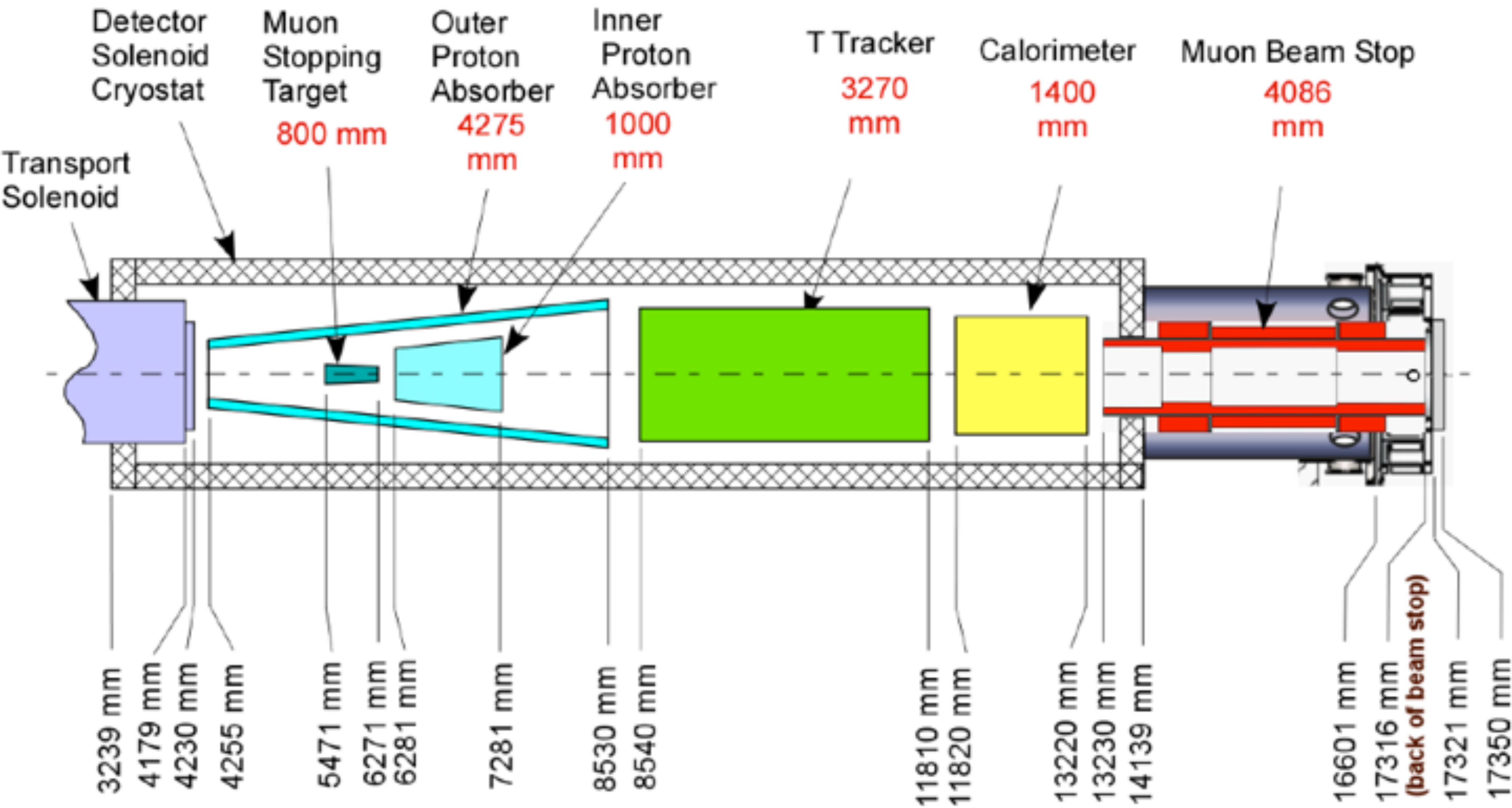
$$\mu N \rightarrow \nu_\mu N' \gamma$$
$$\hookrightarrow e^+ e^-$$

$\Rightarrow$ Want M(Z)-M(Z-1) < signal energy

$\Rightarrow$ Aluminum is nominal choice for Mu2e

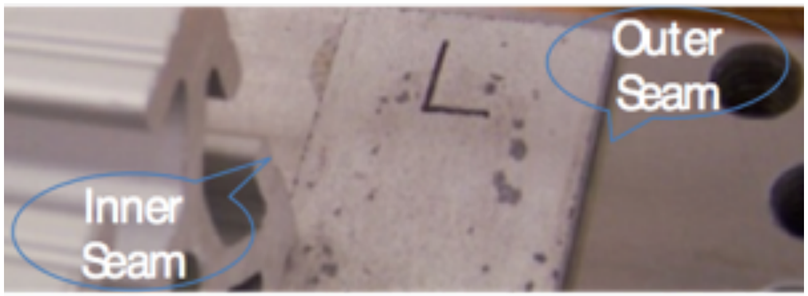
Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound lifetime	Atomic Bind. Energy(1s)	Conversion Electron Energy	Prob decay >700 ns
Al(13,27)	1.0	.88 μs	0.47 MeV	104.97 MeV	0.45
Ti(22,~48)	1.7	.328 μs	1.36 MeV	104.18 MeV	0.16
Au(79,~197)	~0.8-1.5	.0726 μs	10.08 MeV	95.56 MeV	negligible

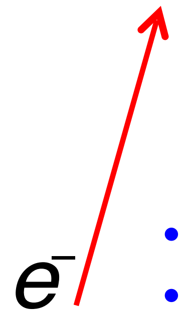
Target and detector complex



Particle tracking technology

- ➢ To achieve the required resolution, must keep mass as low as possible to minimize scattering
- ➢ We've chosen transverse planes of "straw chambers" (21,600 straws)

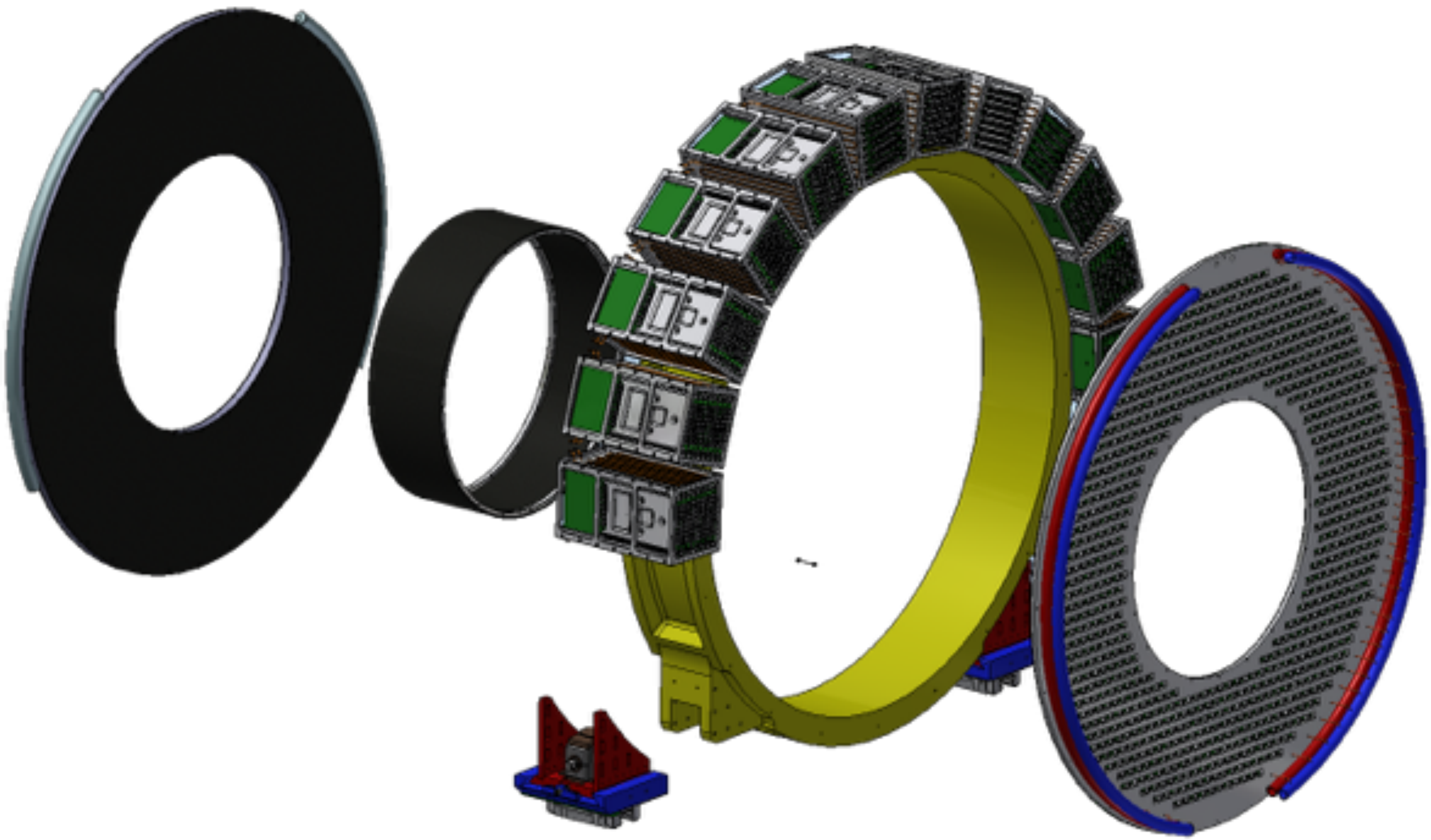




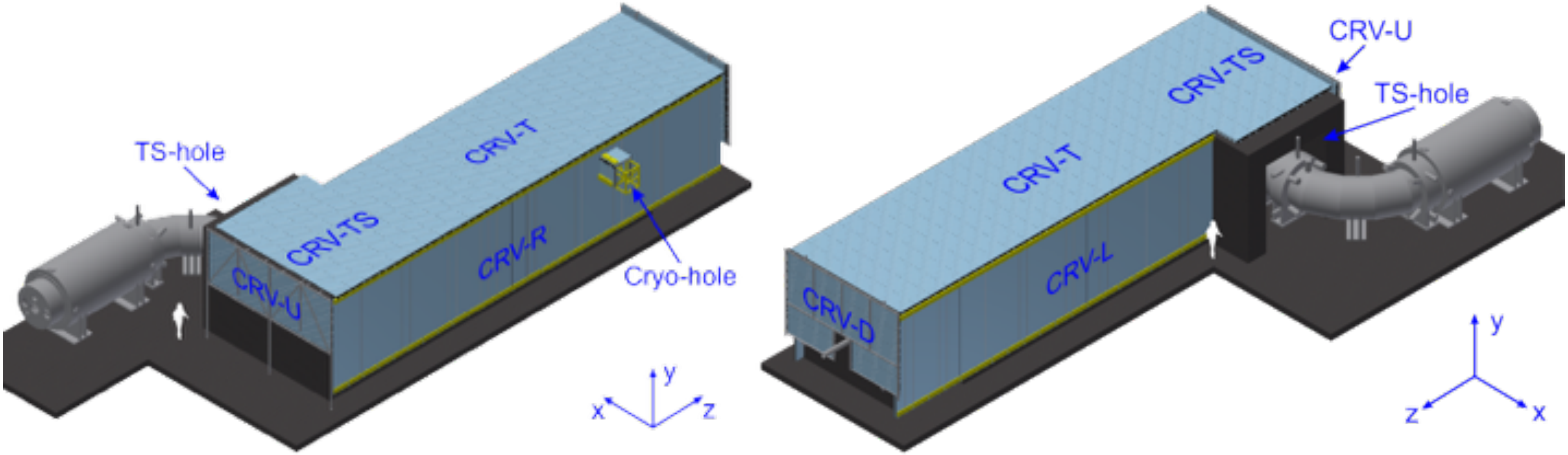
- Track ionizes gas in tube
- Charge drifts to sense wire at center
- Drift time gives precision position

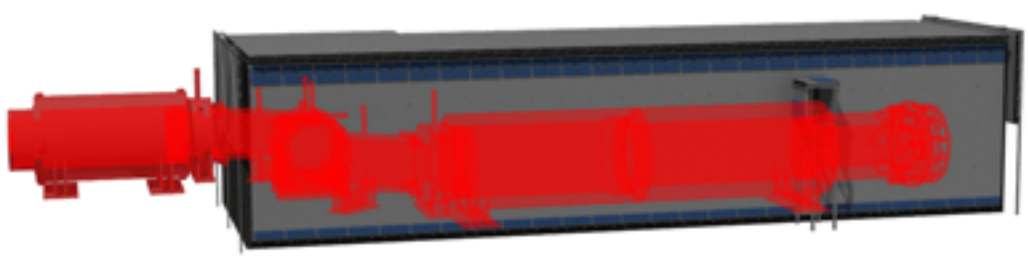
- ➢ Advantages
  - ✓ Established technology
  - ✓ Broken wires isolated
  - ✓ Modular: support, gas, and electronic connections at the ends, outside of tracking volume
- ➢ Challenges
  - ◇ Our specified wall thickness (15 μm) has never been done
  - ◇ Operating in a vacuum may be problematic

A calorimeter annulus: exploded view

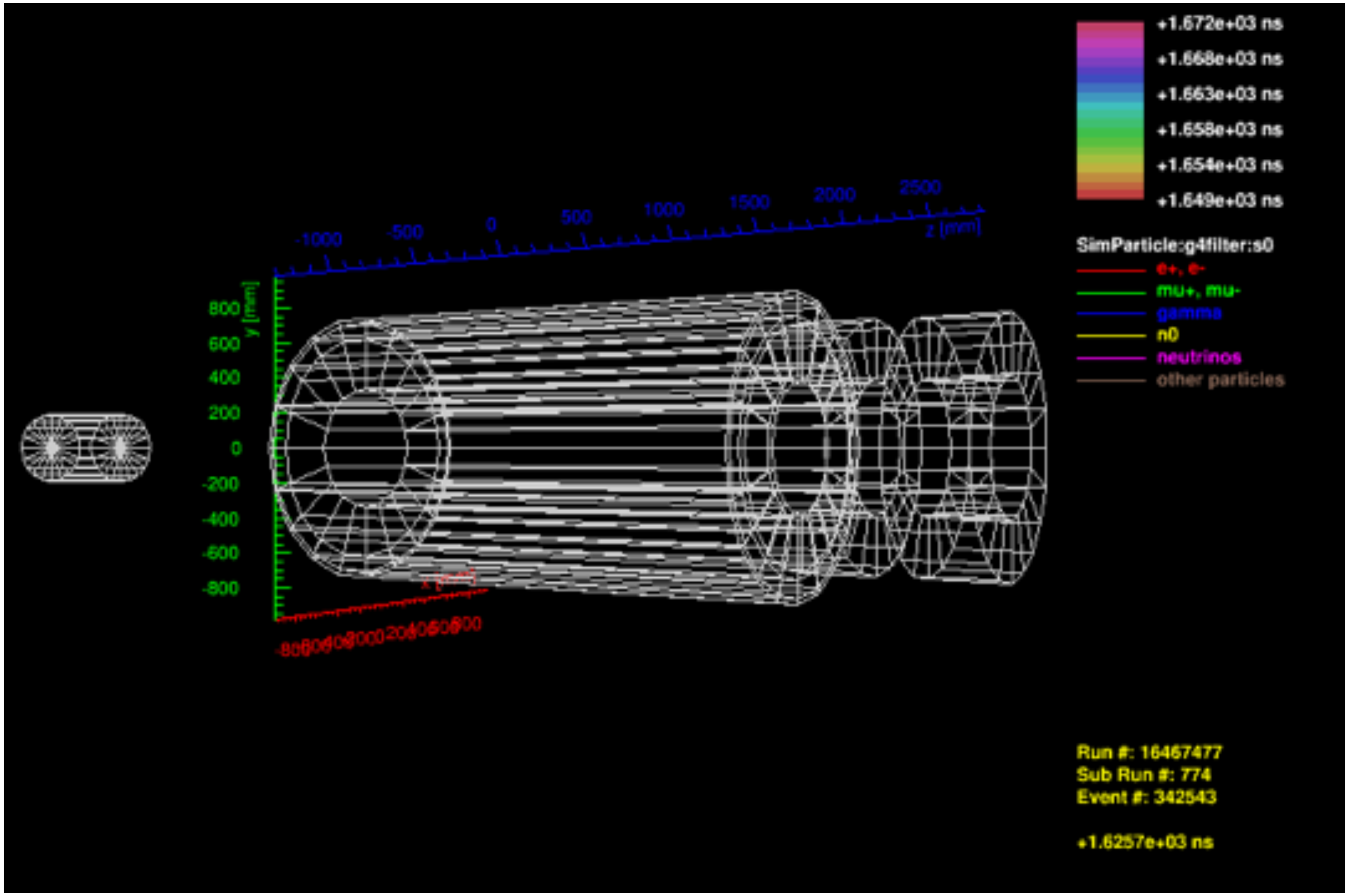


Layout of the CRV

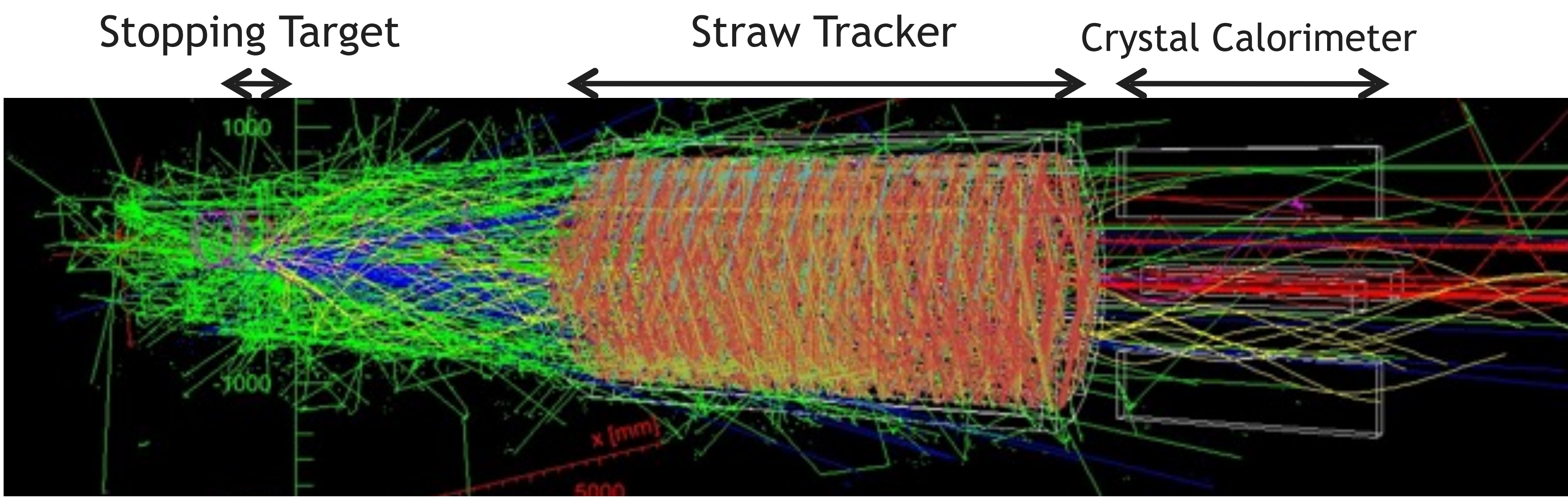




A 105 MeV cosmic-induced electron



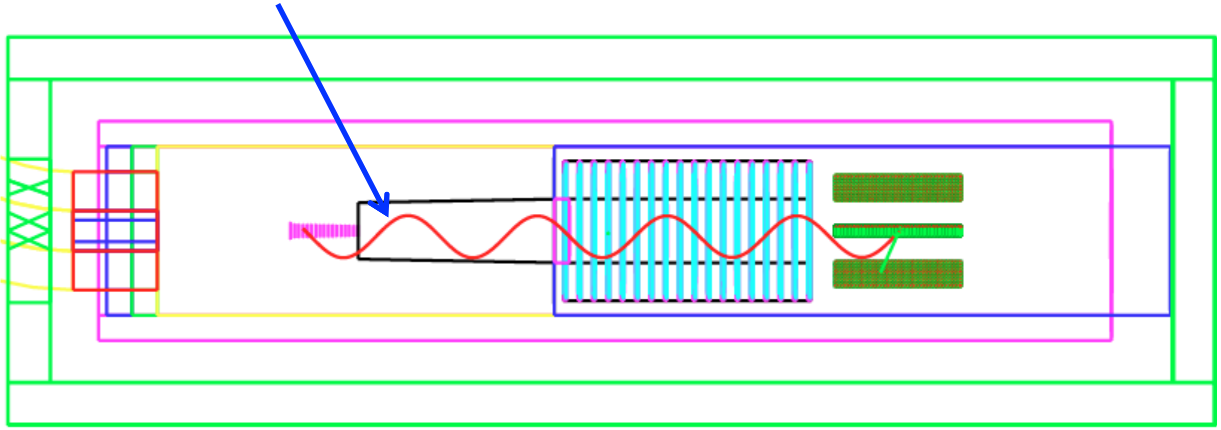
Background overlays

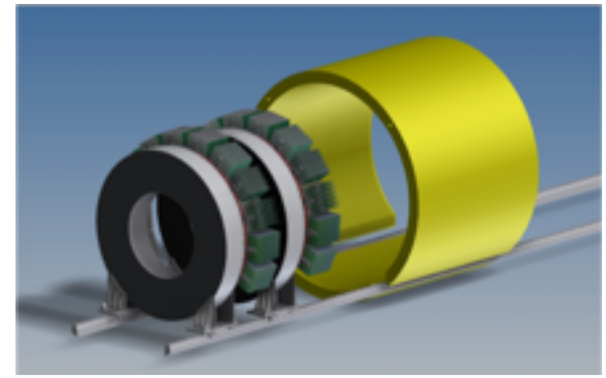


We simulate a full ~1μs, including all the background overlays from the beam flash, μ-capture products, neutrons, etc. and we properly account for contributions from previous bunches

Particle detector

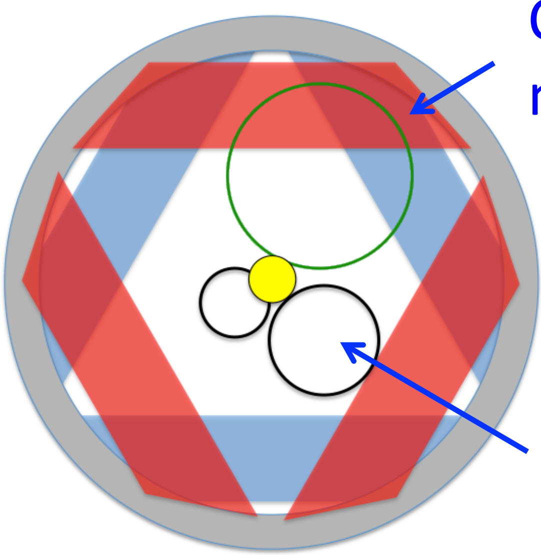
Helical trajectory

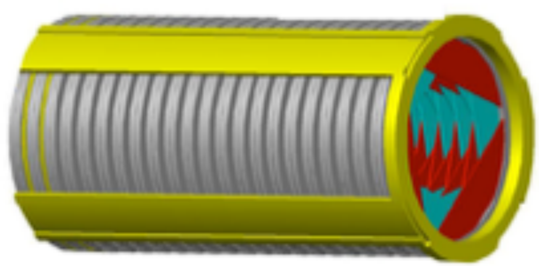




Crystal calorimeter
to tag electrons

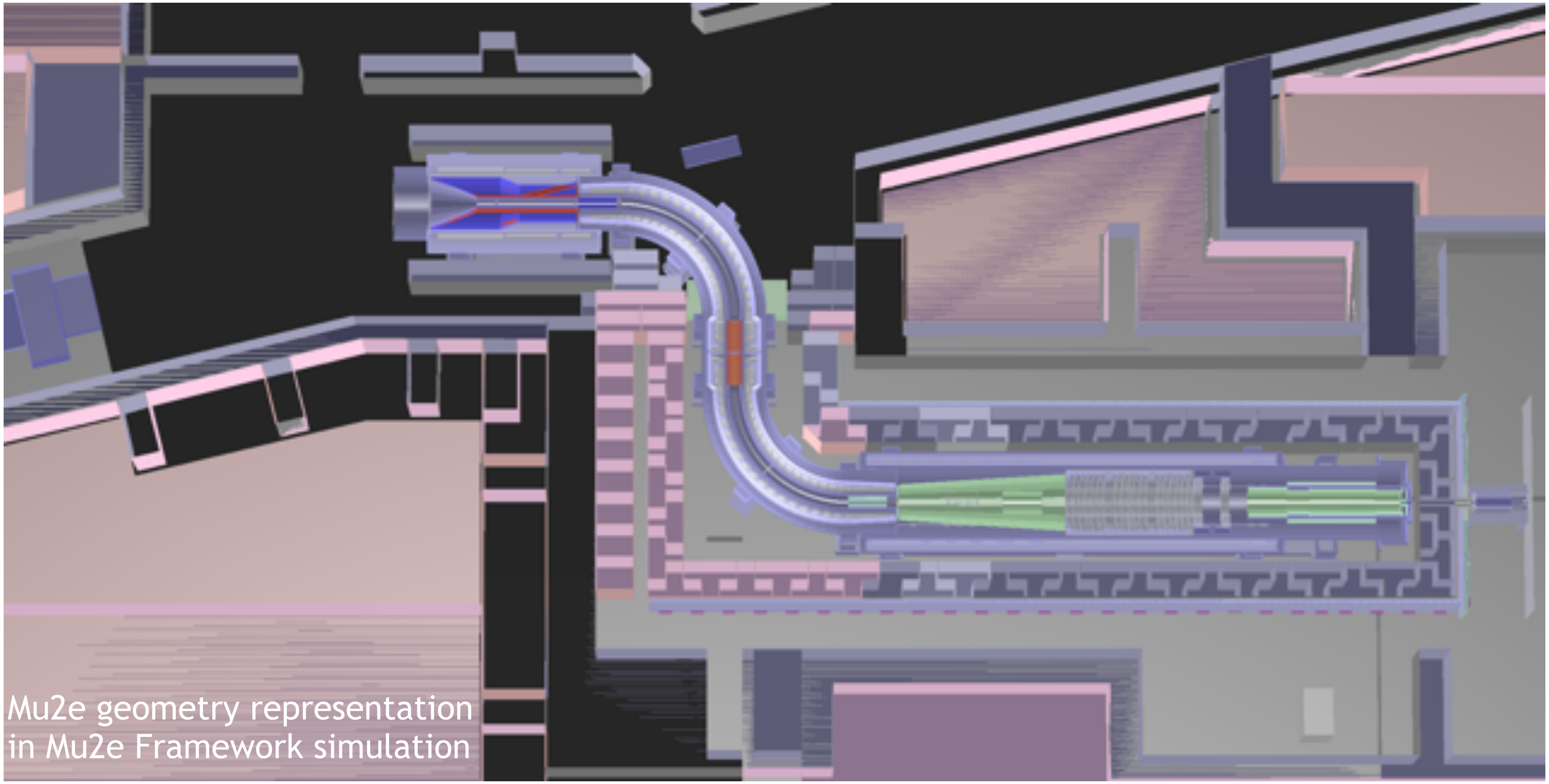
Conversions hit
multiple planes.





Most decays (p_T < 53 MeV/c)
go down the middle (vacuum)

Simulation model



Detailed model of solenoids, targets, detectors, supports, shielding, building, soil and back-fill materials, etc.

Mu2e experimental hall under construction