Study of μ-τ conversion with high-intensity muon beams

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μ-τ and New Physics

- LFV = clear signal for beyond-SM physics
- Space for LFV in many SM extensions (e.g. slepton mixing in SUSY)
- Neutrino oscillations → clear evidence of LFV in neutral lepton sector

What about charged leptons?

- τ-μ/τ-e LFV less constrained than μ-e at present
- We investigate $\mu-\tau$ coupling by studing $\mu-\tau$ conversions of high-intensity muon beams on an active (Si) target

Limits on μ-τ LFV

- Current results:
  - BaBar: ~220 fb^{-1}
  - Belle: ~150 fb^{-1}
  - Upper limits ~ 10^{-7} →
- Also upper limits on BR($B \rightarrow \tau\mu X$) (X=K,π)
- Future projections:
  - BaBar+Belle (2008) ~2000 fb^{-1}
  - Combined data push upper limits down by an order of magnitude to ~ 10^{-8}

Mode	Belle (90% CL)	BaBar (90% CL)
$\tau^- \to e^-\pi^0$	1.9×10^{-7}[2]	
$\tau^- \to e^-\eta$	2.4×10^{-7}[2]	
$\tau^- \to e^-\eta'$	10×10^{-7}[2]	
$\tau^- \to \mu^-\pi^0$	4.1×10^{-7}[2]	
$\tau^- \to \mu^-\eta$	1.5×10^{-7}[2]	
$\tau^- \to \mu^-\eta'$	4.7×10^{-7}[2]	
$\tau^- \to e^-\pi^+\pi^-$	8.4×10^{-7}[3]	1.2×10^{-7}[4]
$\tau^- \to e^-\pi^+K^-$	5.7×10^{-7}[3]	3.2×10^{-7}[4]
$\tau^- \to e^-K^+\pi^-$	5.6×10^{-7}[3]	1.7×10^{-7}[4]
$\tau^- \to e^-K^+K^-$	3.0×10^{-7}[3]	1.4×10^{-7}[4]
$\tau^- \to \mu^-\pi^+\pi^-$	2.8×10^{-7}[3]	2.9×10^{-7}[4]
$\tau^- \to \mu^-\pi^+K^-$	6.3×10^{-7}[3]	2.6×10^{-7}[4]
$\tau^- \to \mu^-K^+\pi^-$	15.5×10^{-7}[3]	3.2×10^{-7}[4]
$\tau^- \to \mu^-K^+K^-$	11.7×10^{-7}[3]	2.5×10^{-7}[4]
$\tau^- \to e^-e^+e^-$	3.5×10^{-7}[5]	2.0×10^{-7}[6]
$\tau^- \to e^-\mu^+\mu^-$	2.0×10^{-7}[5]	3.3×10^{-7}[6]
$\tau^- \to \mu^-e^+e^-$	1.9×10^{-7}[5]	2.7×10^{-7}[6]
$\tau^- \to \mu^-\mu^+\mu^-$	2.0×10^{-7}[5]	1.9×10^{-7}[6]
$\tau \to e\gamma$	3.9×10^{-7}[7]	
$\tau \to \mu\gamma$	3.1×10^{-7}[8]	6.8×10^{-8}[9]

Kanemura et al., hep-ph/0505191

μ-τ couplings and conversion rate

- $\mu-\tau$ conversion via high-energetic μ on a nucleon from $\mu q^{\alpha} \rightarrow \tau q^{\beta}$ (e.g. via Higgs or new gauge bosons exchange)

- Model-independent analysis based on dimension-6 fermionic effective operators

Sher/Turan, PRD69:017302,2004

Black et al., PRD66:053002,2002

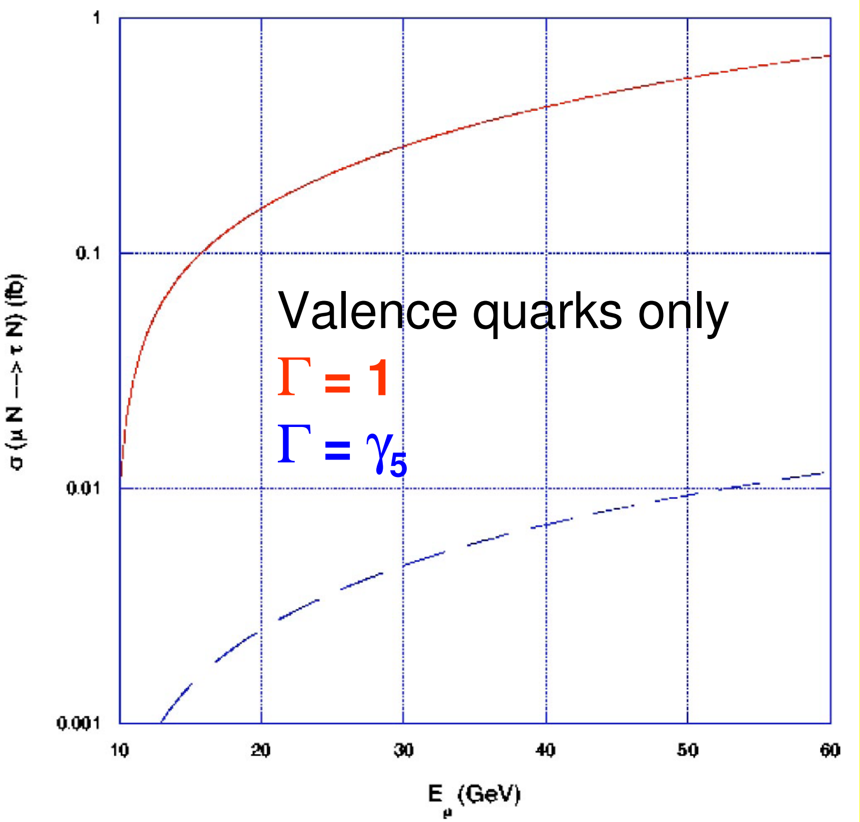
$$L_{int} = 4\pi/\Lambda_{\Gamma,\alpha\beta}{}^2(\bar{\tau}\Gamma\mu)(\bar{q}^{\alpha}\Gamma q^{\beta})+h.c. \quad \Gamma=1,\gamma_5,\gamma_{\sigma},\gamma_5\gamma_{\sigma}$$

Measured upper limits on $\tau\mu$ LFV

→ upper limits on $\Lambda_{\Gamma,\alpha\beta}$

→ upper limit on $\sigma(\mu q^{\alpha} \rightarrow \tau q^{\beta})$

Bound	1	γ_5	γ_σ	$\gamma_\sigma\gamma_5$
$\overline{u}u$	2.6 TeV ($\tau\to\mu\pi^+\pi^-$)	12 TeV ($\tau\to\mu\pi^0$)	12 TeV ($\tau\to\mu\rho$)	11 TeV ($\tau\to\mu\pi^0$)
$\overline{d}d$	2.6 TeV ($\tau\to\mu\pi^+\pi^-$)	12 TeV ($\tau\to\mu\pi^0$)	12 TeV ($\tau\to\mu\rho$)	11 TeV ($\tau\to\mu\pi^0$)
$\overline{s}s$	1.5 TeV ($\tau\to\mu K^+K-$)	9.9 TeV ($\tau\to\mu\eta$)	14 TeV ($\tau\to\mu\phi$)	9.5 TeV ($\tau\to\mu\eta$)
$\overline{s}d$	2.3 TeV ($\tau\to\mu K^+\pi^-$)	3.7 TeV ($\tau\to\mu K^0$)	13 TeV ($\tau\to\mu K^\star$)	3.6 TeV ($\tau\to\mu K^0$)
$\overline{b}d$	2.2 TeV ($B\to\pi\mu\tau$)	9.3 TeV ($B\to\mu\tau$)	2.2 TeV ($B\to\pi\mu\tau$)	8.2 TeV ($B\to\mu\tau$)
$\overline{b}s$	2.6 TeV ($B\to K\mu\tau$)	2.8 TeV ($B_s\to\mu\tau$)	2.6 TeV ($B\to K\mu\tau$)	2.5 TeV ($B_s\to\mu\tau$)
$\overline{t}c$	190 GeV ($t\to c\mu\tau$)	190 GeV ($t\to c\mu\tau$)	310 GeV ($B\to\mu\tau$)	310 GeV ($B\to\mu\tau$)
$\overline{t}u$	190 GeV ($t\to u\mu\tau$)	190 GeV ($t\to u\mu\tau$)	650 GeV ($B\to\mu\tau$)	650 GeV ($B\to\mu\tau$)
$\overline{c}u$	$\star$	$\star$	550 GeV ($\tau\to\mu\phi$)	550 GeV ($\tau\to\mu\phi$)
$\overline{c}c$	$\star$	$\star$	1.1 TeV ($\tau\to\mu\phi$)	1.1 TeV ($\tau\to\mu\phi$)
$\overline{b}b$	$\star$	$\star$	180 GeV ($\Upsilon\to\mu\tau$)	$\star$
$\overline{t}t$	$\star$	$\star$	75 GeV ($B\to\mu\tau$)	120 GeV ($B\to\mu\tau$)



Based on PDG(2000) data:
$\sigma_{max} \approx$1fb at 100 GeV

2005 data: $\sigma_{max} \approx$35ab
2008 data(?): $\sigma_{max} \approx$3.5ab

But potential heavy quarks (c,b) contribution at high μ energies (study $c\bar{c}\to\tau\mu X$ and $b\bar{b}\to\tau\mu X$?)

Kanemura et al., PLB607:165,2005

A physical model: SUSY MSSM

– Scalar and pseudoscalar interactions (Higgs)
  - Couple only to L-handed μ (produce R-handed τ)
  - Couple only to d-type quarks
  - Couplings $\propto m_q$
    - → at large Q^2 (E_μ>50 GeV) significant contribution from b quark
    - → for lower E_μ s quark contribution dominates
  - Upper limit on s-quark coupling from BR($\tau \rightarrow \mu\eta$)

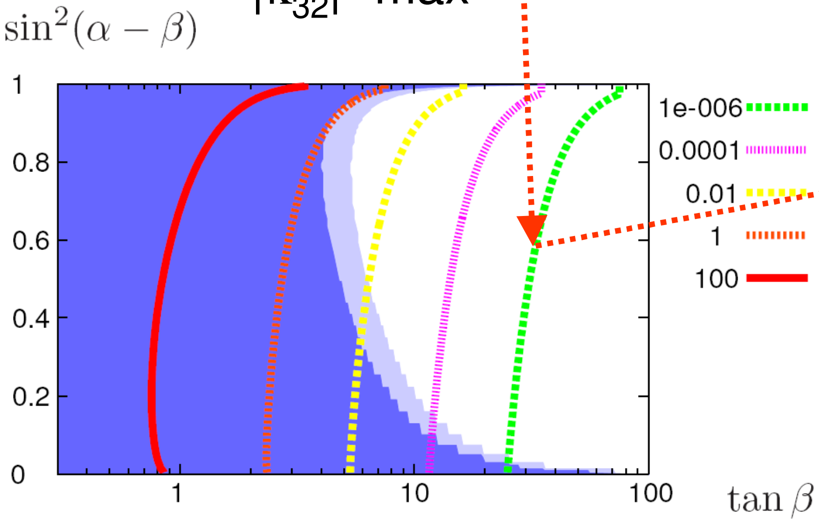
– Vector, axial vector and tensor interactions (gauge-bosons)
  - No enhancement from b-quark contribution
  - → Suppressed for E_μ>50 GeV wrt Higgs mediated LFV

$$\mathcal{L}_{\tau\ell_i} = -\frac{\kappa_{3i} m_\tau}{v\cos^2\beta}\left\{\cos(\alpha-\beta)h^0 + \sin(\alpha-\beta)H^0 - iA^0\right\}(\overline{\tau_R}\ell_{Li})$$

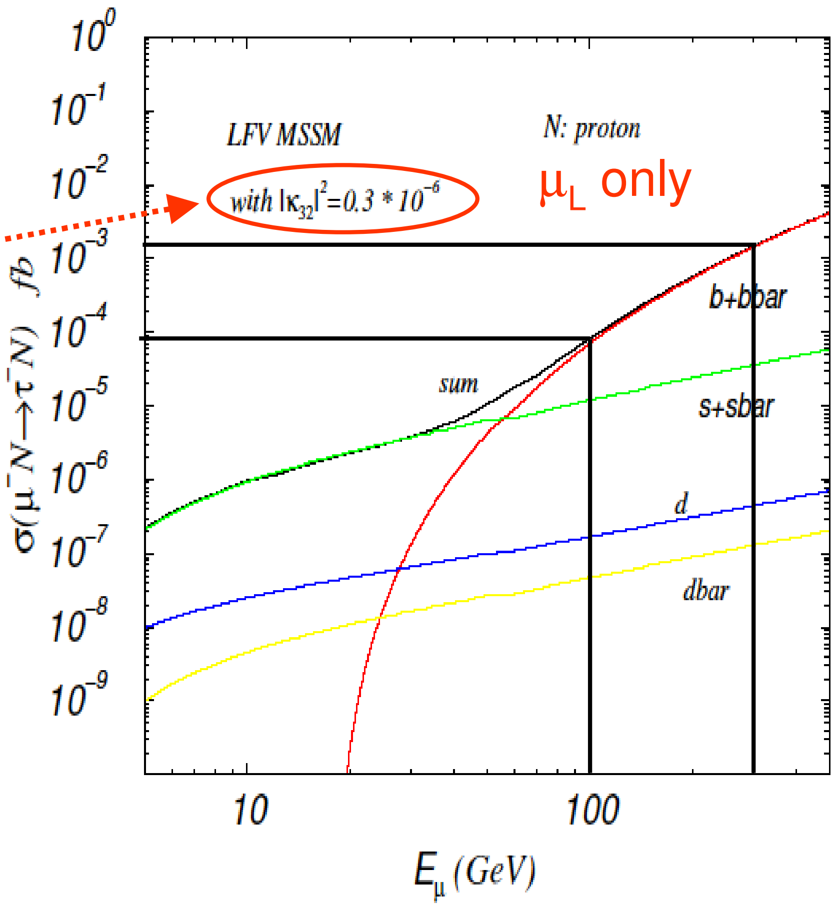
$$\mathrm{Br}(\tau \xrightarrow{A} \mu\eta) \simeq \frac{9G_F^2(F_\eta^8)^2 m_\eta^4 m_\tau^3 \tau_\tau}{128\pi}\frac{1}{m_A^4}|\kappa_{32}|^2 \tan^6\beta < 3.4\times10^{-7}$$ ($1.5*10^{-7}$ at present)

$$|\kappa_{32}|^2 < 0.3\times10^{-6}\times\left(\frac{m_A}{150[\mathrm{GeV}]}\right)^4\times\left(\frac{60}{\tan\beta}\right)^6.$$

$|\kappa_{32}|^2$ max



m(H^0)=m($H^\pm$)=m(A)=350GeV
m(h^0)=120 GeV
$|\kappa_{32}|^2_{max}$ up to 10^{-2} for low tanβ



Signal estimate

- Working hypothesis:
  - 10 cm Si target [330 planes, 300 μm-thick, 1m^2 area]
  - E_μ=100-300 GeV → σ~0.1-1ab (could be x10^4 higher?)

- Signal events produced in 1 year:

$N = N_\mu * \sigma * 23.3g\ cm^{-2} / 1.66*10^{-24}g$

$= N_\mu * \sigma(ab) * 1.4*10^{-17}$

- To produce 1000 events/year:
  - σ = 0.1(100) ab → $N_\mu = 6*10^{20}$ ($6*10^{17}$) μ/yr

→muon flux = $6*10^{14}$ ($6*10^{11}$) $\mu/s/m^2$ in the spill if

1) duty cycle=10s
2) delivery time=10^7s/yr

Backgrounds

- Beam-related events
  - Can be vetoed (more later)
- Physics
  - Dominant contribution from Deep Inelastic Scattering: $\sigma \sim O(10)$nb @ $Q^2 > 4 GeV^2$
    - $6 \cdot 10^{14}$ (10^{11}) μ/s → 10^8 (10^5) events/s
    - Trigger: in worst scenario, need rejection >~ 10^5
  - Other processes with lower cross sections (eg $\mu e \rightarrow \mu e$, $\mu N \rightarrow \nu_\mu X$) could be relevant at analysis level and are outside the scope of this study

Which μ energy?

- Signal cross section enhancement from $b\bar{b}$ contribution favors E_μ >~ 60 GeV
  - E_μ = 100GeV → low W → virtual b →no free B's in the final state
  - E_μ = 300GeV → high W → b-flavored hadrons in the final state

- Heavy flavor production in the final state will affect the trigger and analysis strategy

Tools

- To study signal and bkg events, we have customized the LEPTO (DIS) generator
  - Implemented elementary cross section (S+PS) proposed by Kanemura et al. (PLB607:165,2005)
  - Alternative cross section formulae can be implemented
- The generator describes only muon-nucleon scattering

  → how to extend to heavy nuclei including nucleus fragmentation/form factor?

Tools (2)

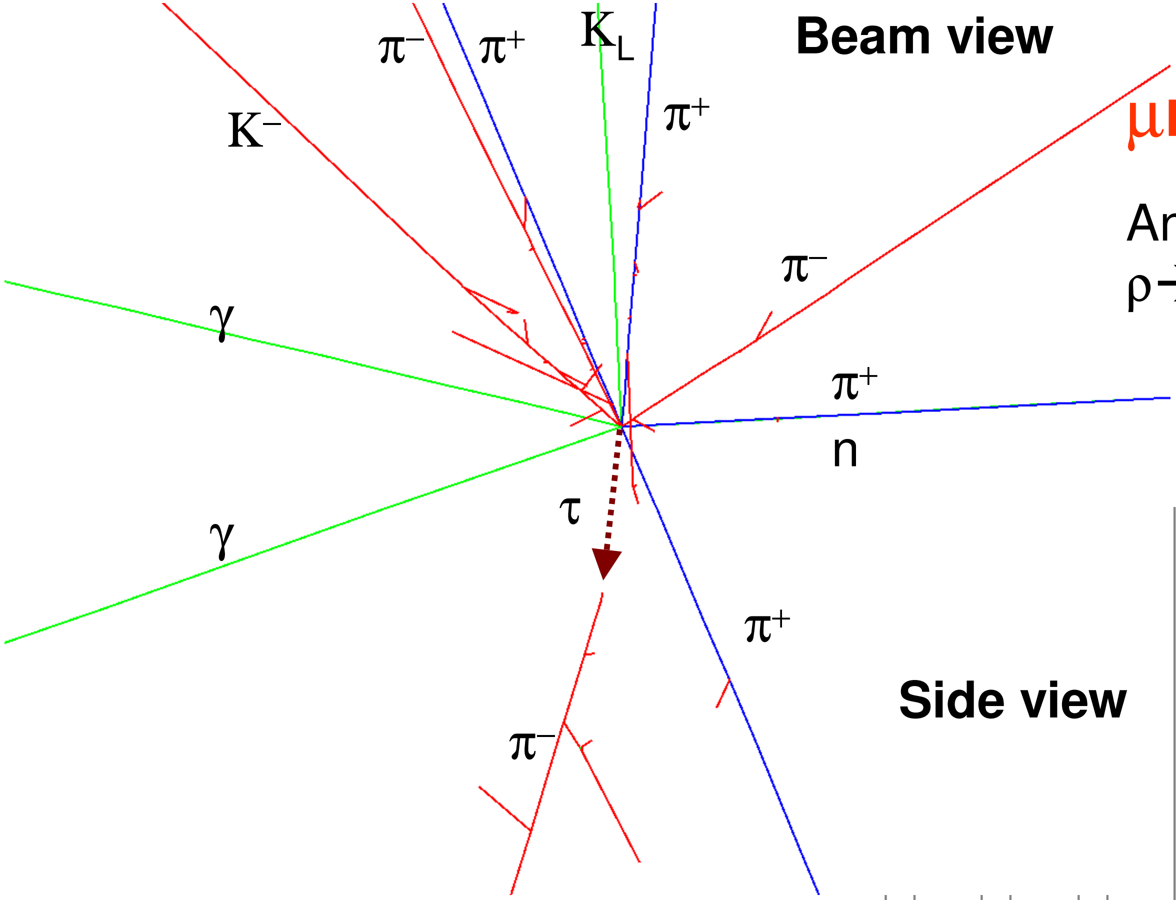
- The GEANT4 HepEvt interface has been modified in order to read the generator output (momenta, vertices, ..) dumped in an ASCII file
  - → All the ingredients needed for a realistic simulation of the trigger and detector response are in place

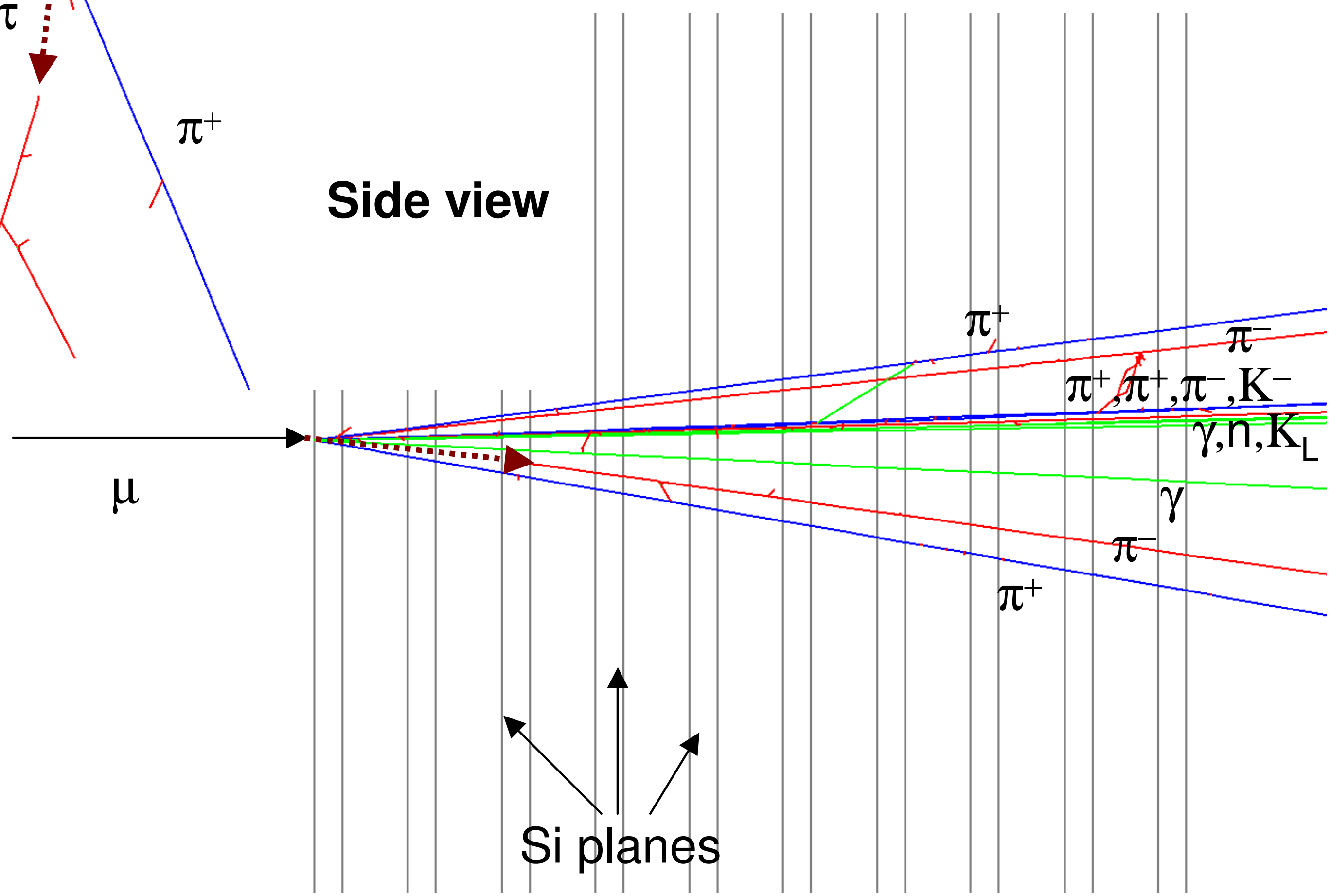
- Further improvements:
  - τ decay currently simulated by Jetset, τ polarization not taken into account → replace with Tauola

$\mu n \rightarrow \tau\ n$ anti-$K^{*0}\ \pi^+\ \rho^0\ \rho^-\ K^{*+}$

Anti-$K^{*0} \rightarrow K^-\pi^+$ $\quad$ $K^{*+} \rightarrow K_L\pi^+$

$\rho \rightarrow \pi\pi$ $\quad$ $\pi^0 \rightarrow \gamma\gamma$





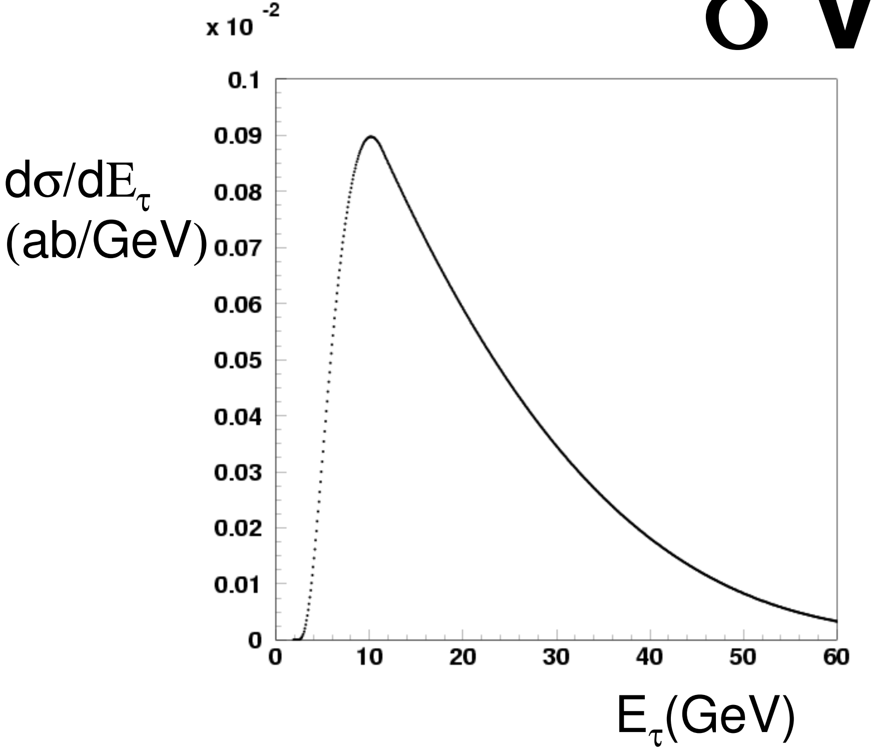
GEANT4

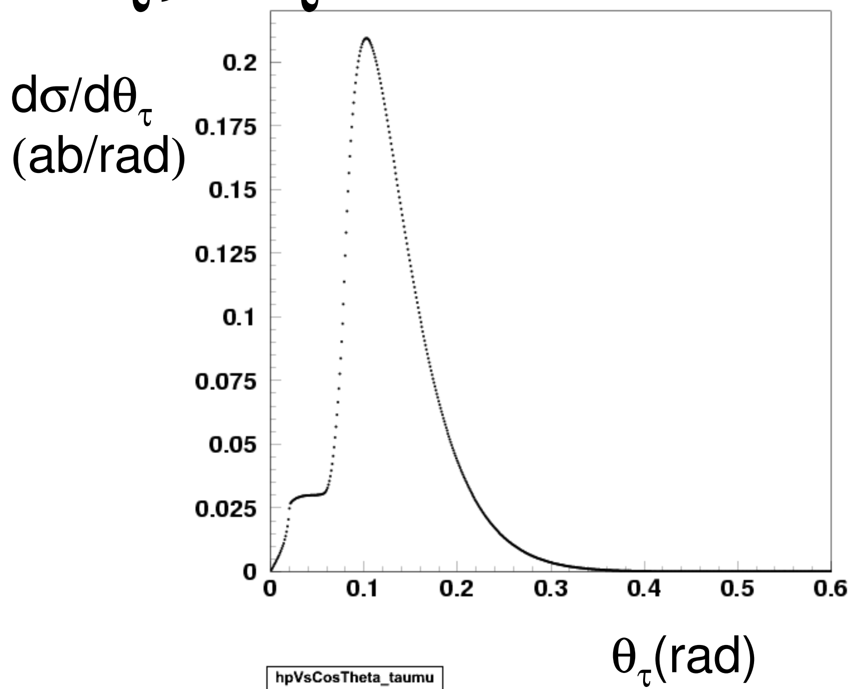
$\tau \rightarrow \pi\nu$

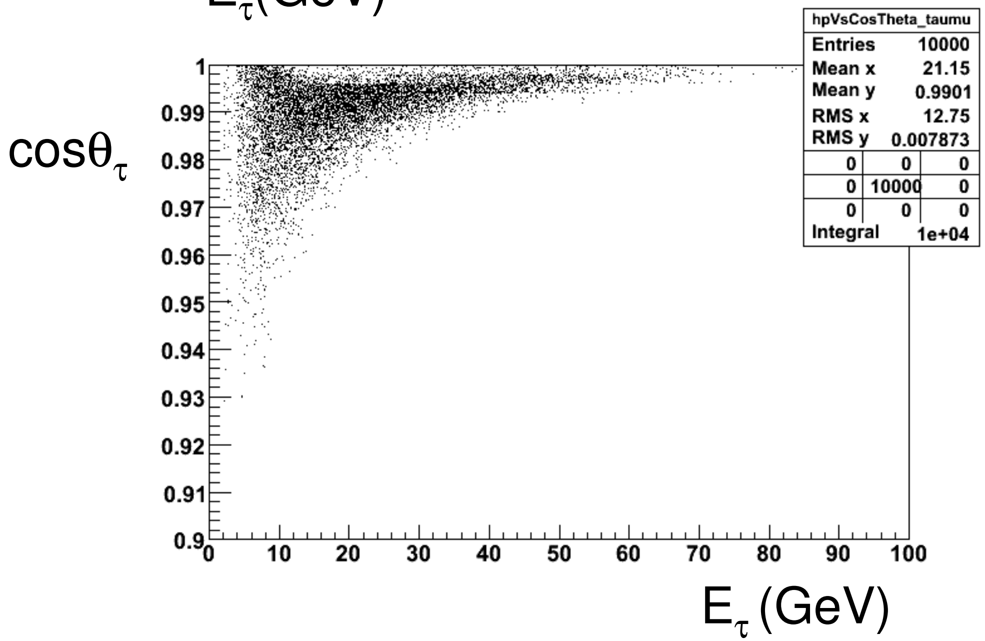
No B field

σ vs E_τ, θ_τ

E_μ=100GeV

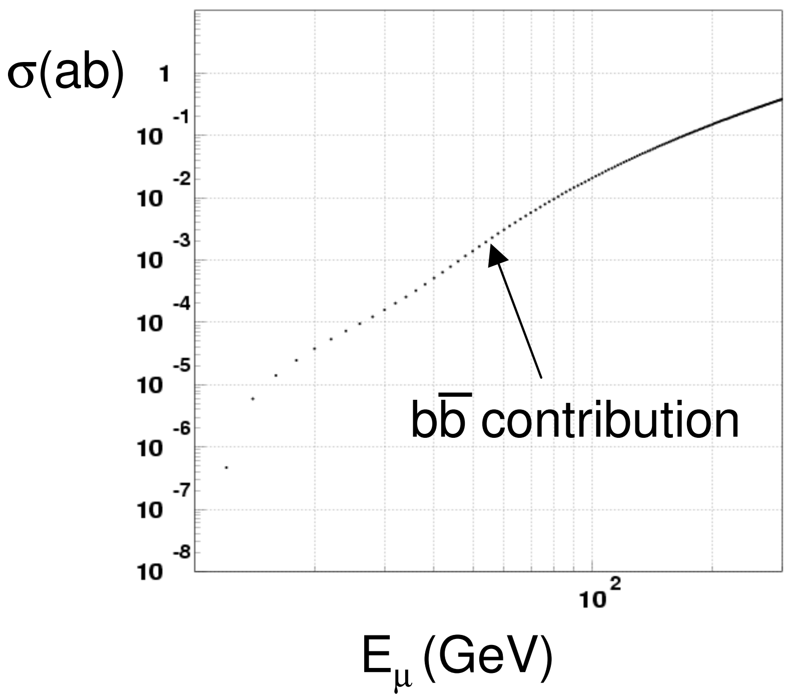




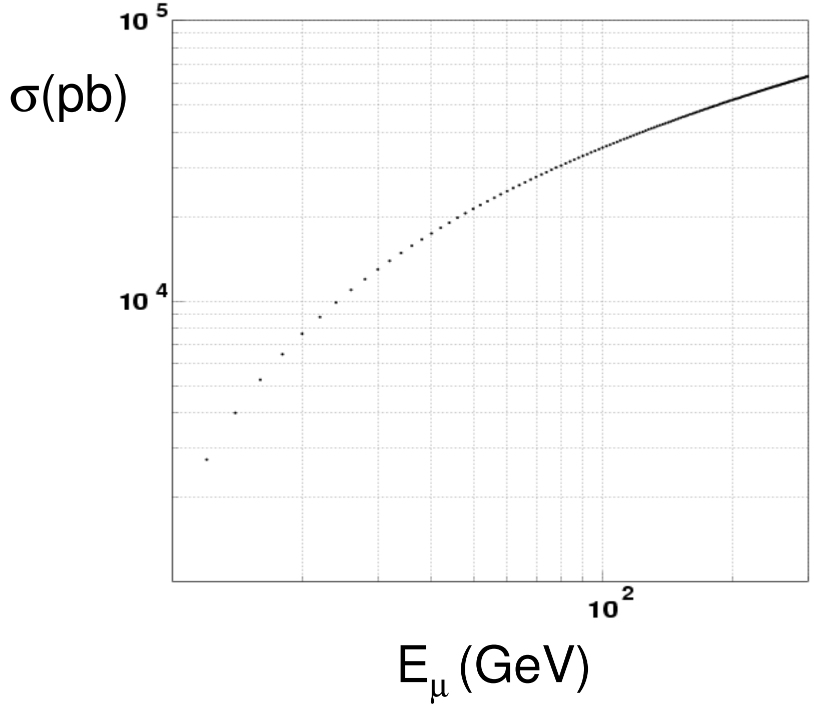


Cross sections vs μ energy

$\mu N \rightarrow \tau X$

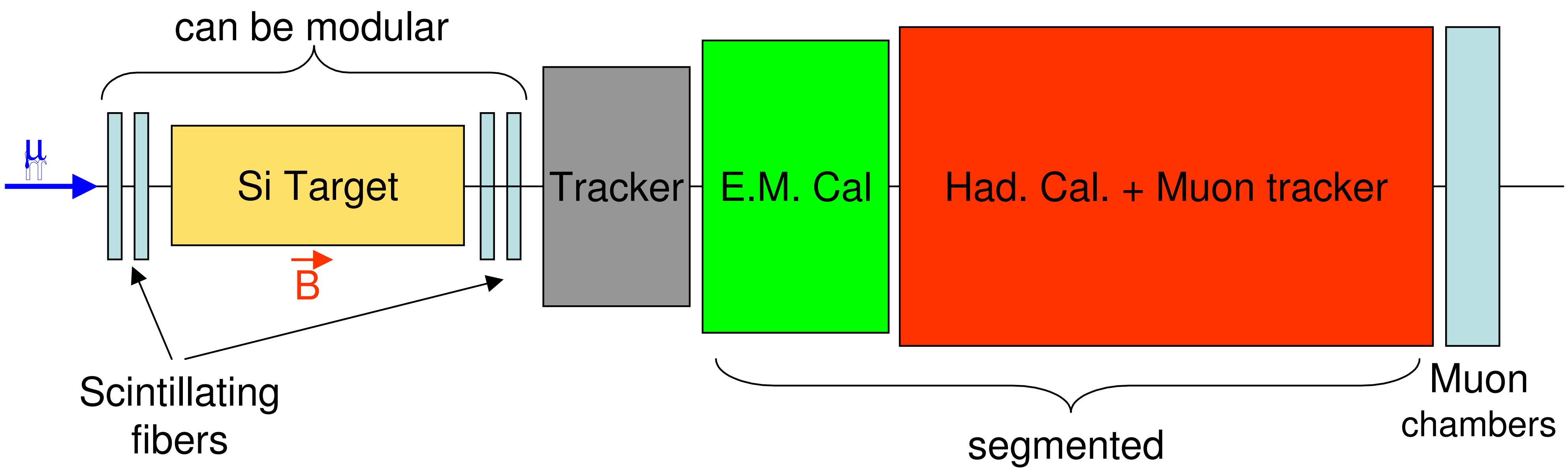


DIS



$Q^2 > 4 GeV^2$

A conceptual design



NOT TO SCALE!

- Calorimetric sections needed for μ/e/hadron separation
- Si active target provides vertex reconstruction

→can be modular

- Scintillating fibers to reduce beam-associated background
- Particle trajectories and interactions are visualized throughout the whole detector

Some basic requirements

- To reject beam-related events ($\sim 10^{14}$ μ/s/m^2)
  - ns coincidence
  - <0.1cm^2 granularity ($\phi<3.3$mm)
  - →Scintillating fibers could be an option
  - →With 10^{11} μ/s/m^2 a coarser granularity obtained with plastic scintillator strips would be as good

- Calorimeters:
  - Emphasis on shower development and shape in order to separate μ/e/hadrons
  - →longitudinal and transversal segmentation

Si target

- $1m^2$ surface → full beam tracking
- 10cm thickness (330 planes, 300μm) → μτ conversion rate
- Granularity: compromise between
  - Point resolution driven by τ lifetime (cτ~90μm) $\propto A^{-1/2}$
  - Occupancy $\propto A^{-1}$
  - Bandwidth $\propto A$

With 100*100 μm^2 pixels + digital readout:

→ Point resolution ~ 30μm

→ Occupancy ~ 10^{-2} in 10 ns (for 10^{14} $\mu/s/m^2$)

→ Bandwidth: with a L1 trigger rejection factor ~10^5, 10^{14} (10^{11}) $\mu/s/m^2$, 10s duty cycle & 10 cm x $1m^2$ Si target → $7*10^4$ (10^1) Gb/s

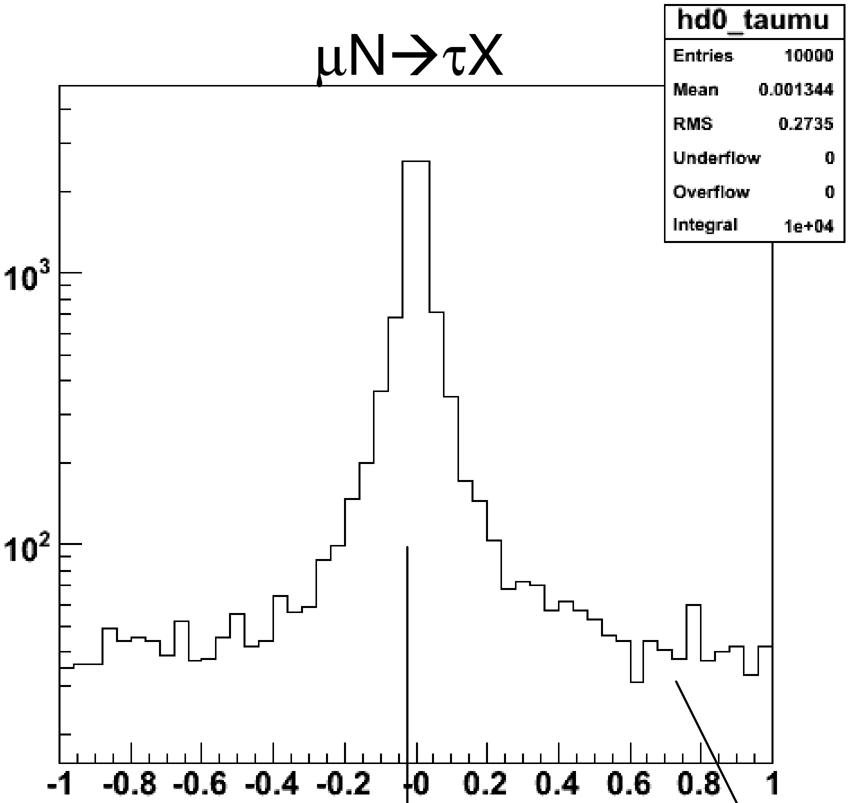
→Extremely challenging with current technology!

Discriminating variables

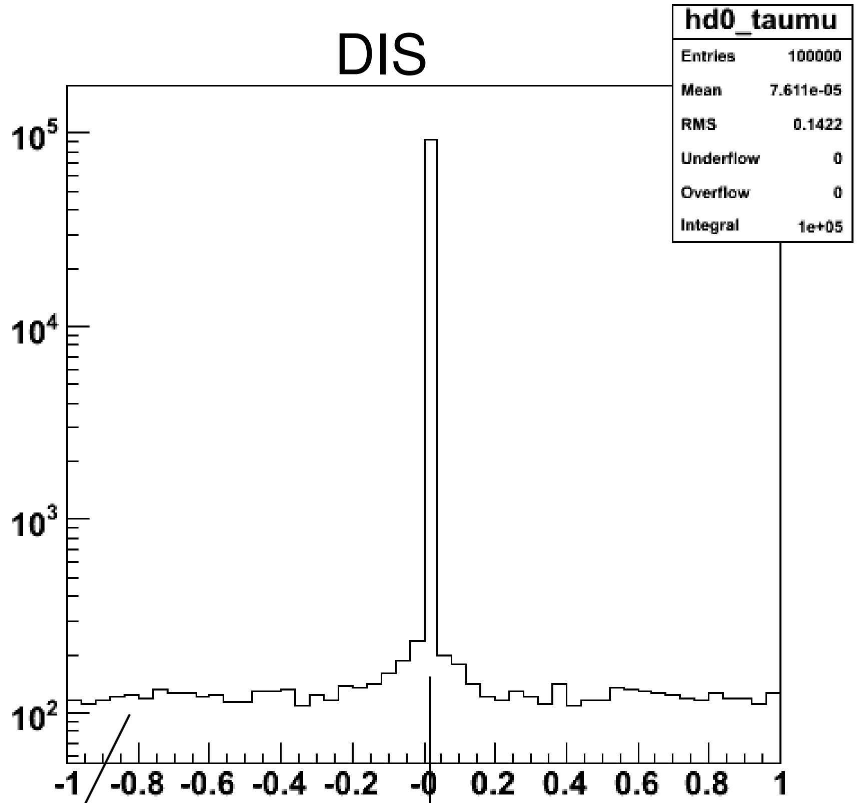
- Muon-ID [μ chambers + E.M./Had Cal]
- p, p_T of charged tracks
- Impact parameter
- Total missing energy>0 (ν from τ decay)

  – Other will be investigated

Impact parameter



d_0 (mm)



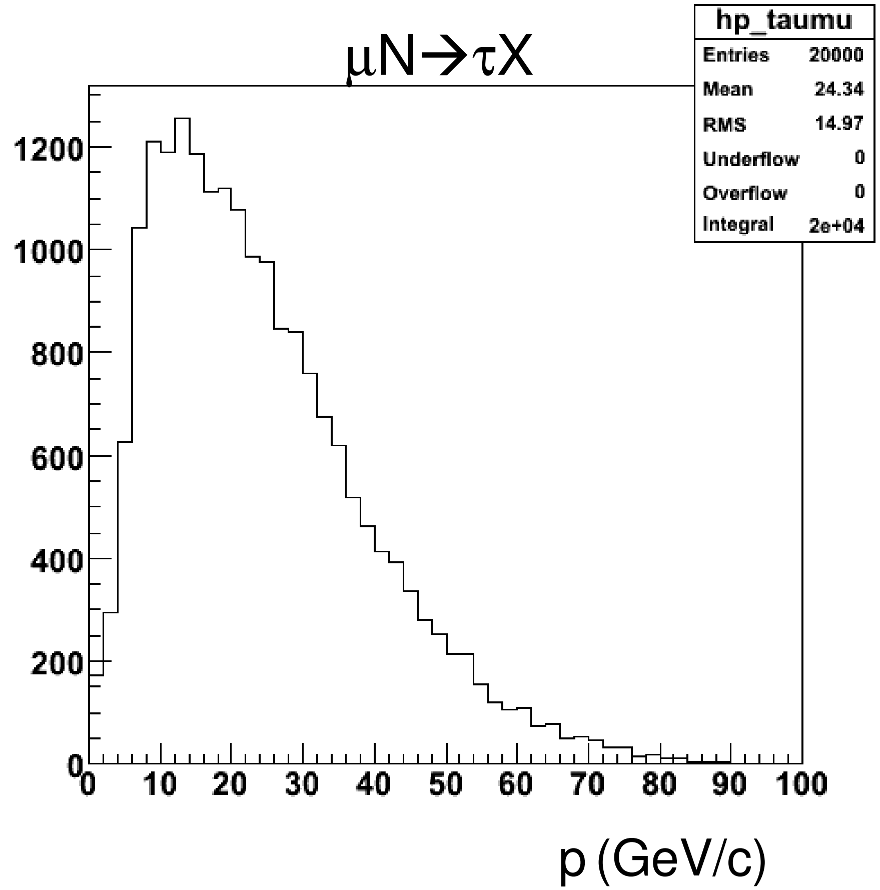
d_0 (mm)

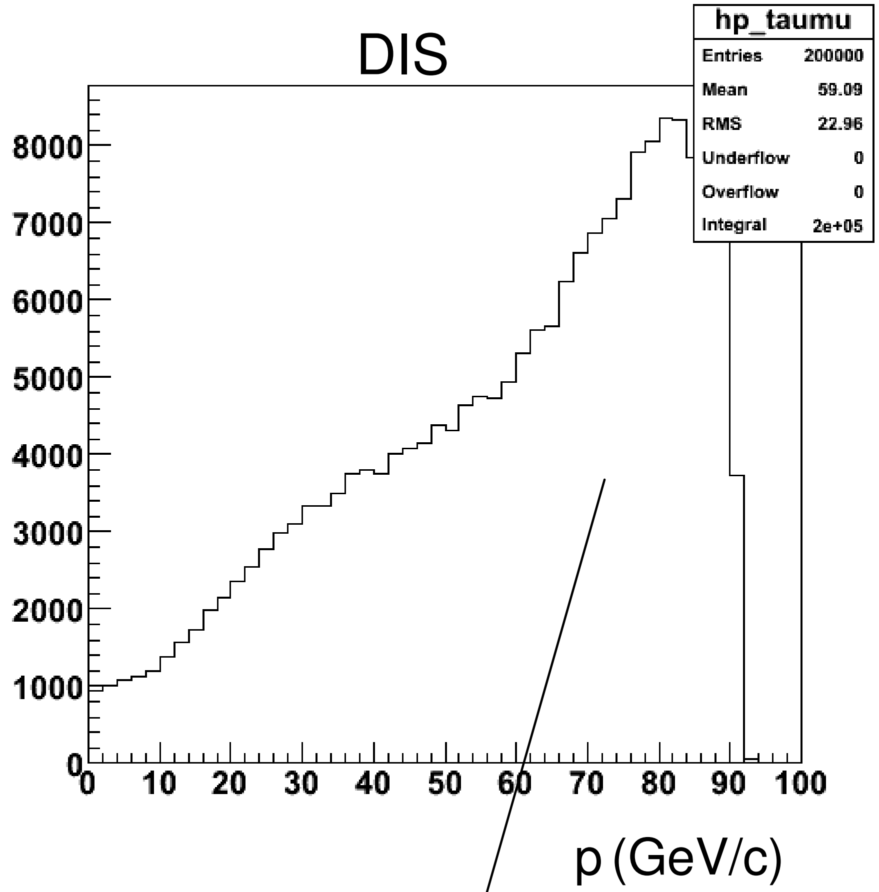
Short-lived V0s

τ decays
Peak RMS = $c\tau = 90\mu m$

Scattered μ and prompt particles
in the hadronic recoil

Highest momentum in the event

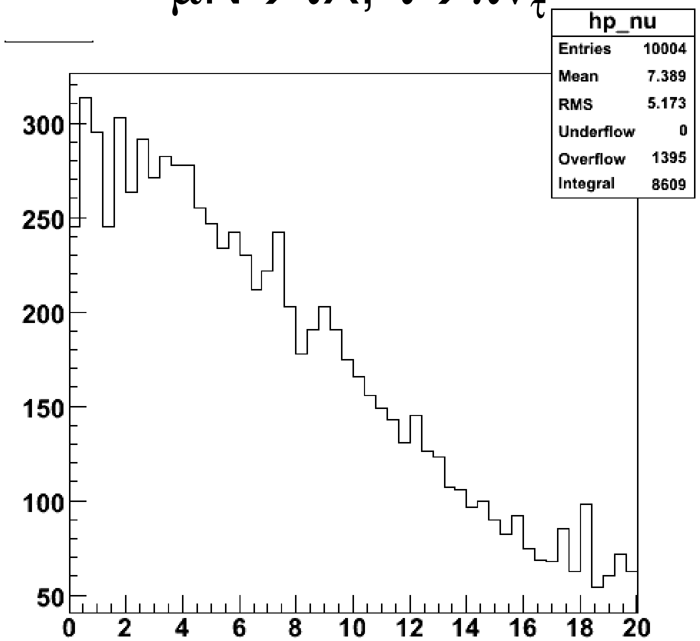




Scattered μ emitted preferentially with high momentum and small angle

Missing (ν) energy

$\mu N \rightarrow \tau X$, $\tau \rightarrow \pi \nu_\tau$



E_ν (GeV)

- τ decays always produce at least 1ν
- No ν produced in most DIS events → missing energy virtually 0

But: detector resolution, especially due to neutral hadrons, needs to be studied

Conclusion

- A $\mu-\tau$ conversion event generator, interfaced with a full-detector simulation, has been set-up
- A basic design for a detector has been described, with some ideas for a 1st-pass background rejection strategy
- The strength of the detector lies in
  - Capability to visualize the full event
  - Modularity of the active target allows for different sensitivity/cost combinations

  at the price of high granularity and fast readout
- A detailed detector design must be simulated and different background sources identified and studied

INPUTS	PDG(2000)	PDG(2005)	PDG(2008)?	
BR(tau->mu pi0)	4.00E-06	4.10E-07	4.10E-08	
BR(tau->mu eta)	9.60E-06	1.50E-07	1.50E-08	
BR(tau->mu K0)	1.00E-03	1.90E-06	1.90E-07	
BR(tau->mu rho)	6.30E-06	6.30E-06	6.30E-07	
BR(tau->mu phi)	7.00E-06	7.00E-06	7.00E-07	
BR(tau->mu K*)	7.50E-06	7.50E-06	7.50E-07	
BR(tau->mu pi pi)	8.20E-06	2.90E-07	2.90E-08	
BR(tau->mu K K)	1.50E-05	2.50E-07	2.50E-08	
BR(tau-> mu K pi)	7.50E-06	3.20E-07	3.20E-08	
BR(B->mu tau)	8.30E-04			
BR(Bs->mu tau)	1.00E-01			
BR(B-> K mu tau)	5.00E-02			
BR(B-> pi mu tau)	5.00E-02			
BR(t-> u mu tau)	2.80E-01			
OUTPUTS(2000)	S	PS	A	V
uu (TeV)	2.6	11.7	11.3	12.4
dd (TeV)	2.6	11.7	11.3	12.4
ss (TeV)	1.5	9.9	9.5	14.3
sd (TeV)	2.3	3.7	3.6	12.8
cu (TeV)			0.55	0.55
cc (TeV)			1.1	1.1
tu (TeV)	0.19	0.19	0.65	0.65
tc (TeV)	0.19	0.19	0.31	0.31
tt (TeV)			0.75	0.12
bd (TeV)	2.2	9.3	2.2	8.2
bs (TeV)	2.6	2.8	2.6	2.5
bb (TeV)			0.18	
OUTPUTS(2005)	S	PS	A	V
uu (TeV)	6.00E+00	2.07E+01	2.00E+01	1.24E+01
dd (TeV)	6.00E+00	2.07E+01	2.00E+01	1.24E+01
ss (TeV)	4.17E+00	2.80E+01	2.69E+01	1.43E+01
ds (TeV)	5.06E+00	1.77E+01	1.72E+01	1.28E+01
OUTPUT(2008)	S	PS	A	V
uu (TeV)	1.07E+01	3.68E+01	3.55E+01	2.21E+01
dd (TeV)	1.07E+01	3.68E+01	3.55E+01	2.21E+01
ss (TeV)	7.42E+00	4.98E+01	4.78E+01	2.54E+01
ds (TeV)	9.00E+00	3.15E+01	3.07E+01	2.28E+01